Physikalisch-Technische Bundesanstalt
Braunschweig and Berlin
National Metrology Institute

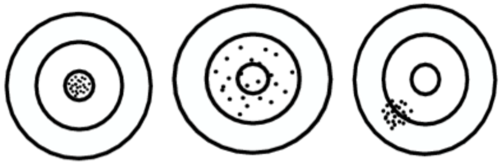
Transportable optical lattice clocks

Christian Lisdat

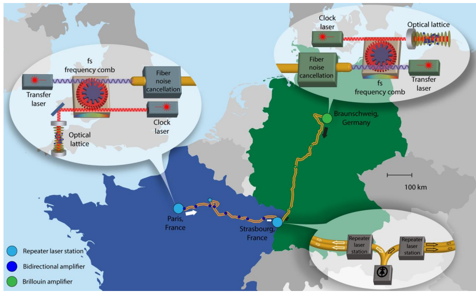
ESA Topical Team Meeting, 22. – 23.10.2018, Munich

Outline:

- ► Few words about (optical) clocks

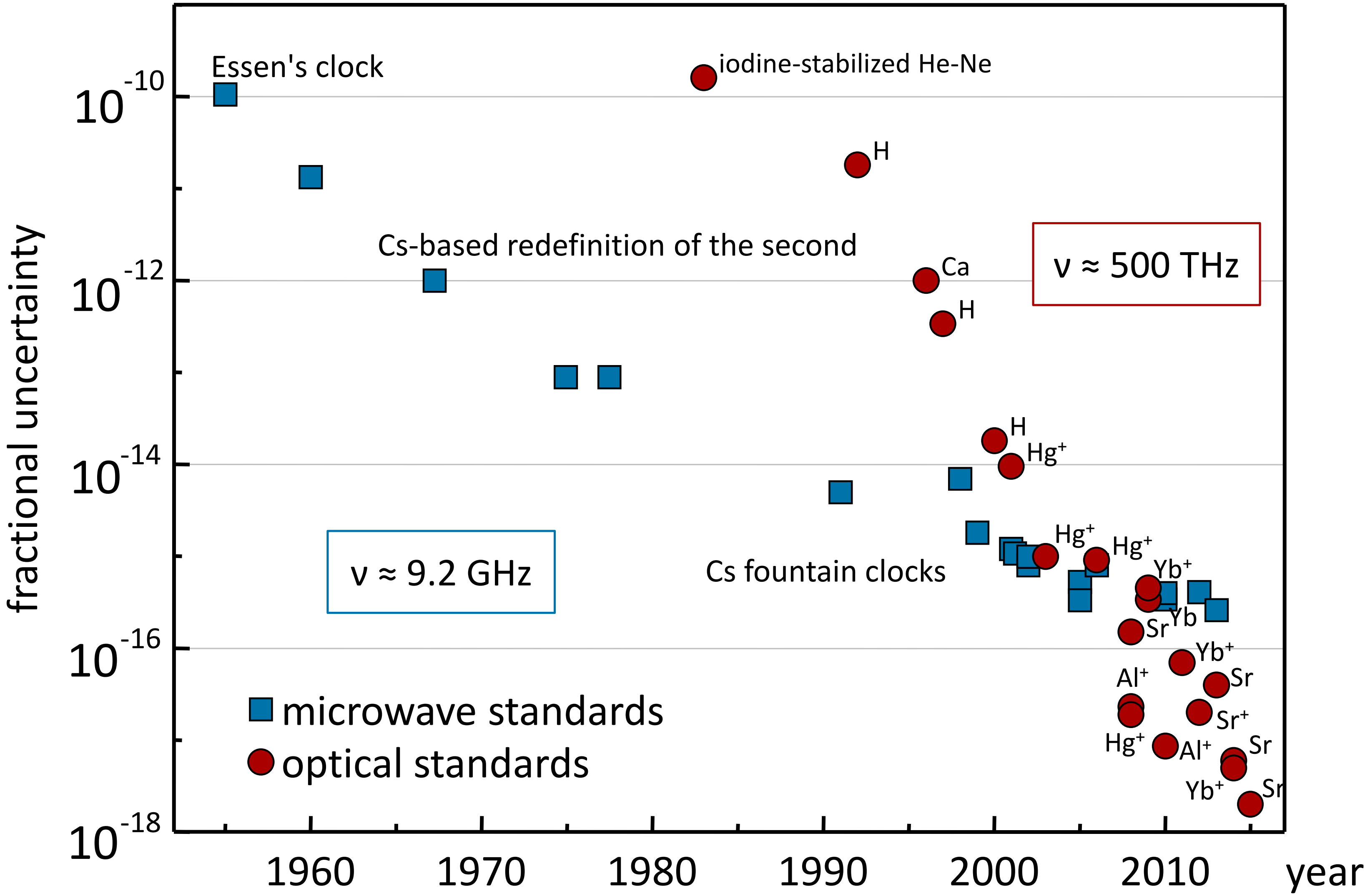


- ► Clocks in the lab: examples of experiments

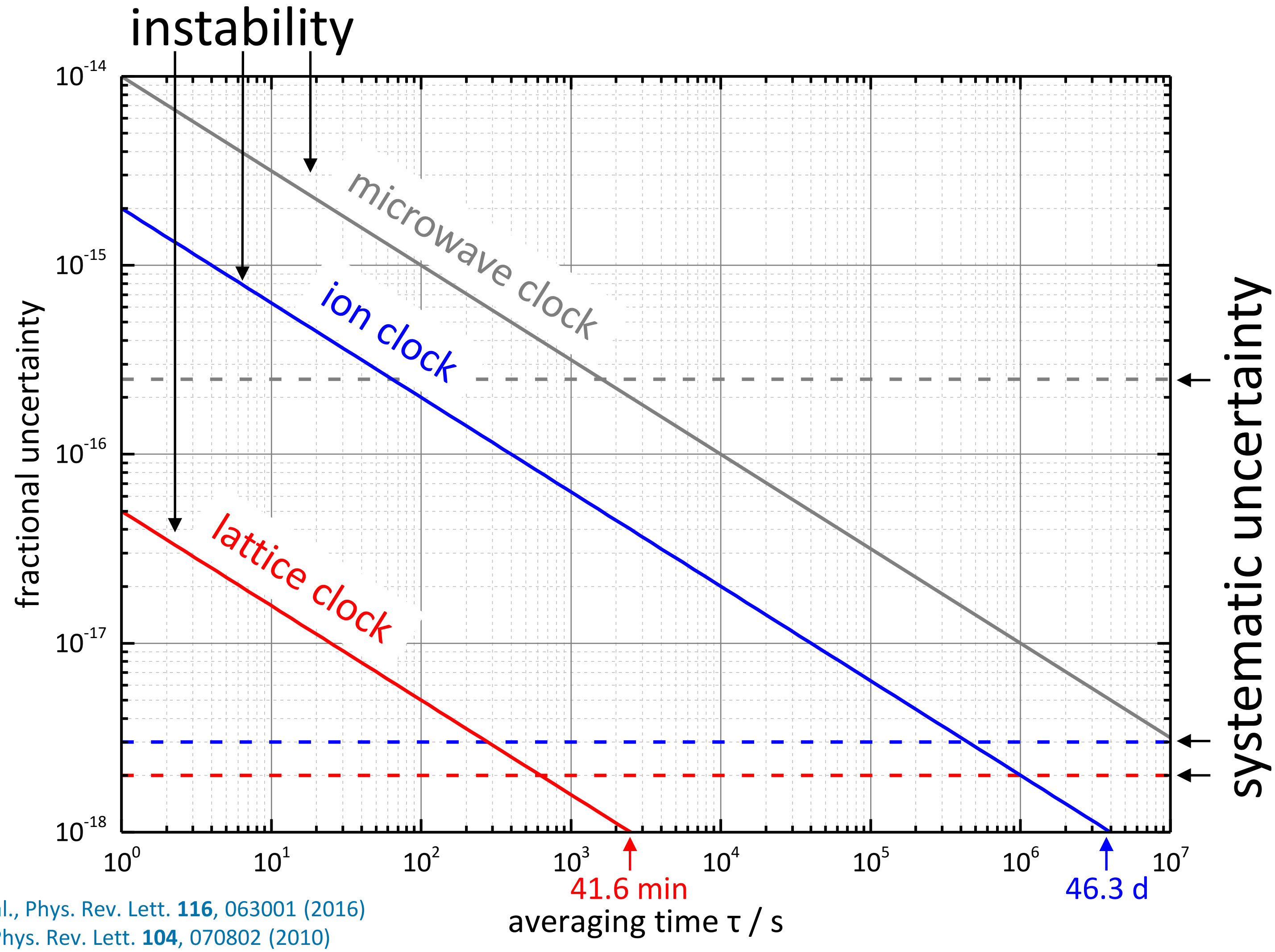


- ► Campaigns with our transportable optical lattice clock

Evolution of atomic clocks



Best clock performances



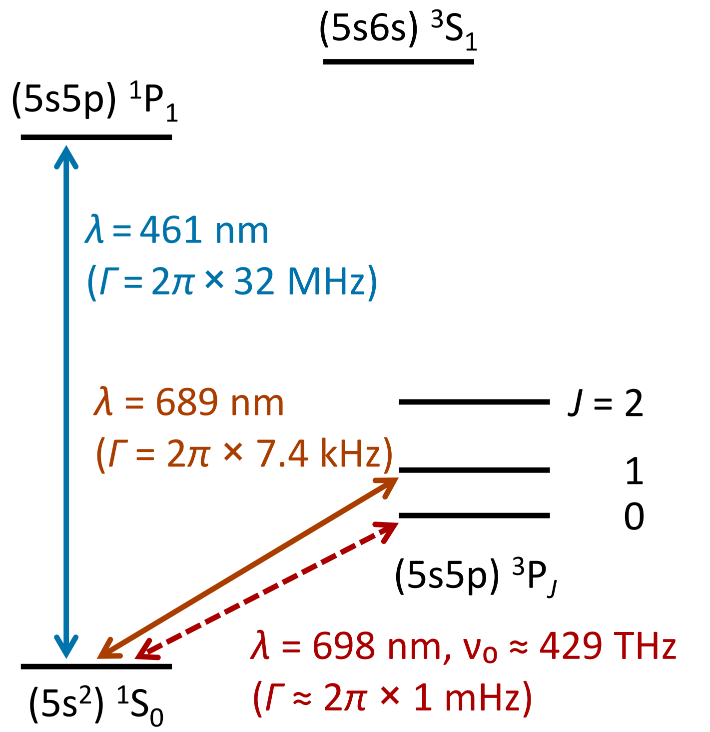
N. Huntemann et al., Phys. Rev. Lett. **116**, 063001 (2016)
C. W. Chou et al., Phys. Rev. Lett. **104**, 070802 (2010)
T. Nicholson et al., Nature Com. **6**, 6896 (2015)
M. Schioppo et al., Nature Photonics **11**, 48 (2017)

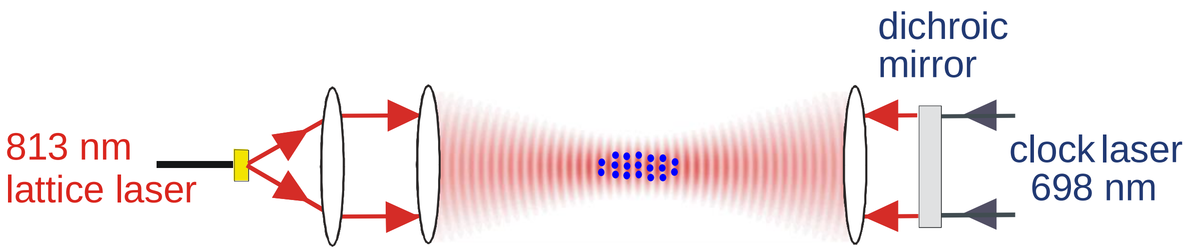
Strontium lattice clock

Experimental sequence

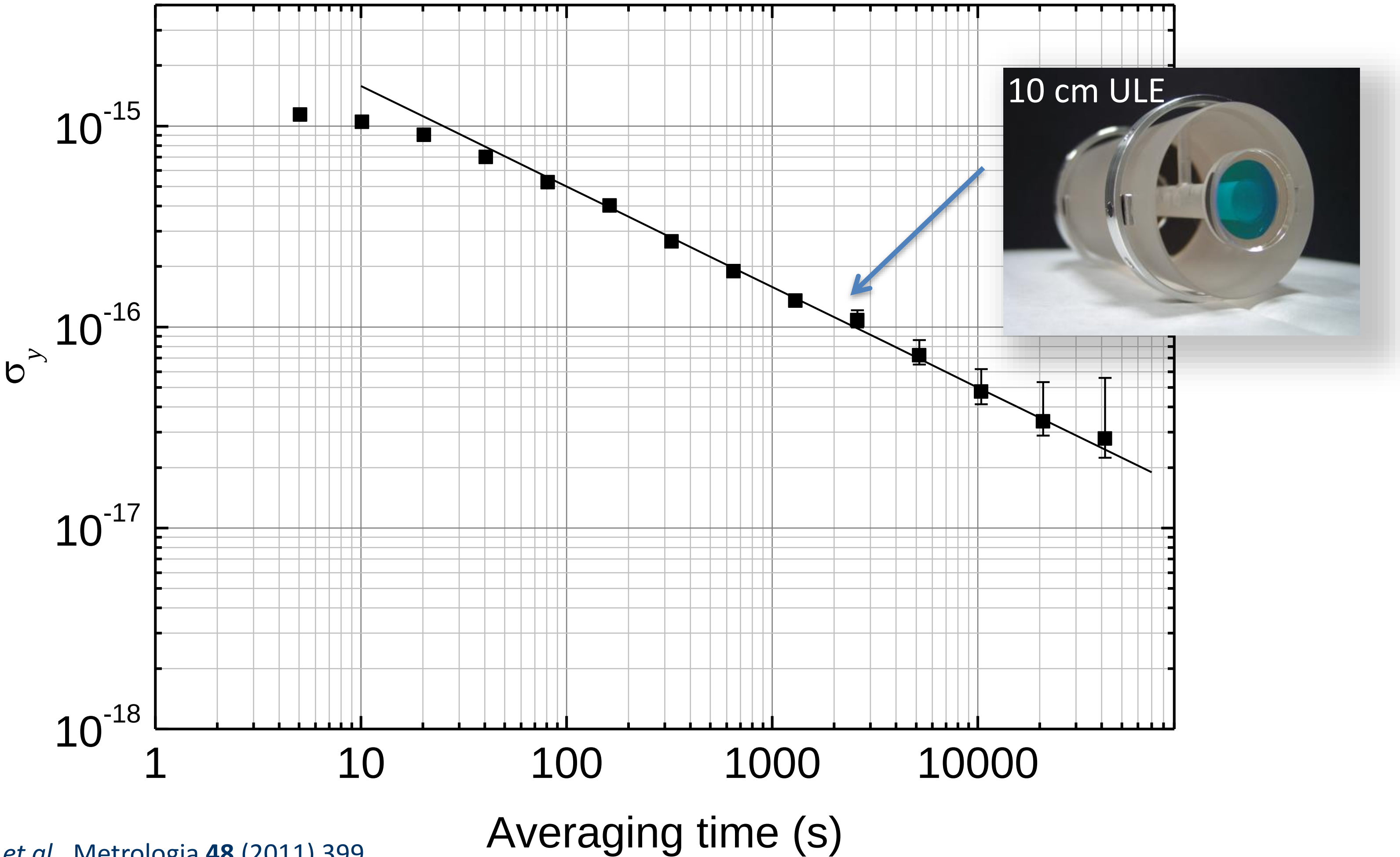
200 ms	Zeeman slower 1st stage MOT (461 nm), $T \backsim$ mK
90 ms	2nd stage MOT (689 nm)
90 ms	3rd stage MOT (689 nm), $T \backsim$ µK
65 ms	state preparation in 1D optical lattice
0.8 s – 2.6 s	Rabi interrogation (698 nm) in 1D optical lattice
	balanced detection

Partial level diagram





Importance of the clock laser



St. Falke *et al.*, Metrologia **48** (2011) 399 ,
Ch. Hagemann *et al.*, IEEE Trans. Instr. Meas. **62** (2013) 1556
A. Al-Masoudi *et al.*, PRA **92**, 063814 (2015)

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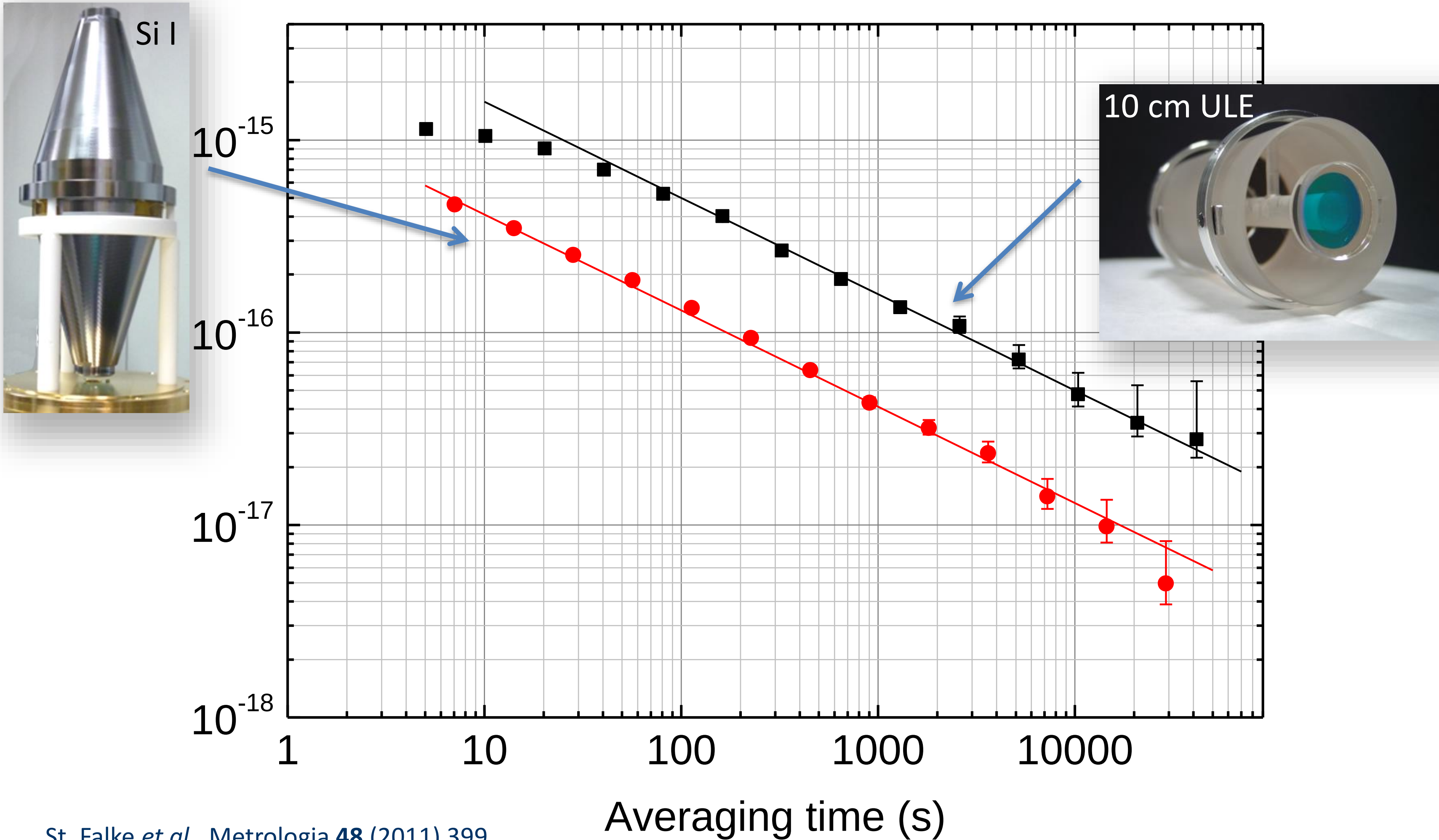

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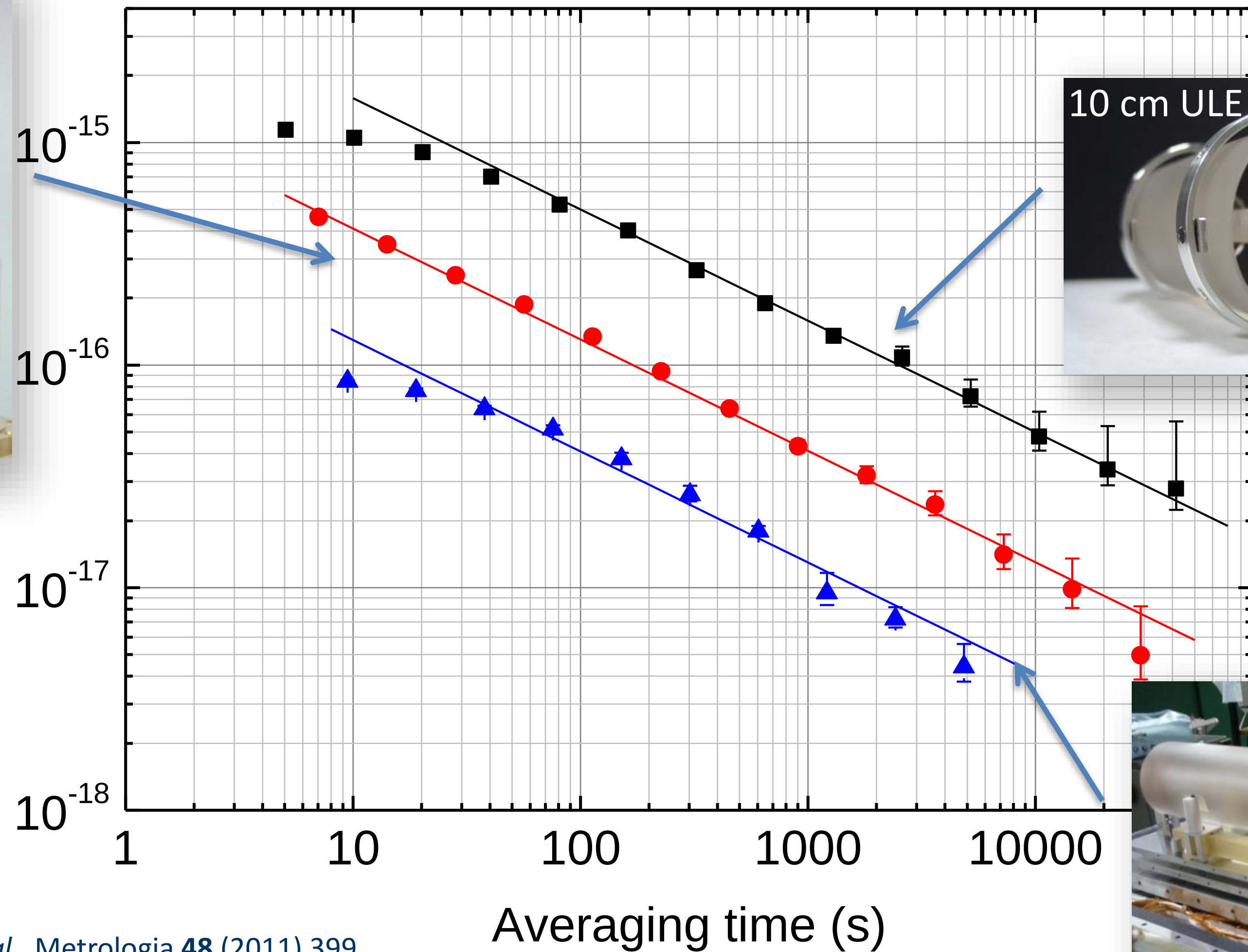

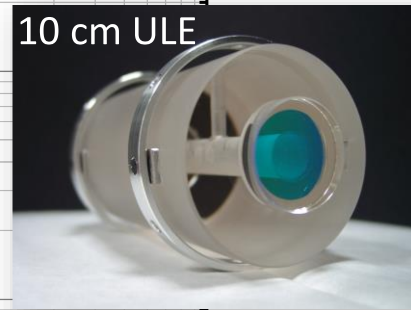

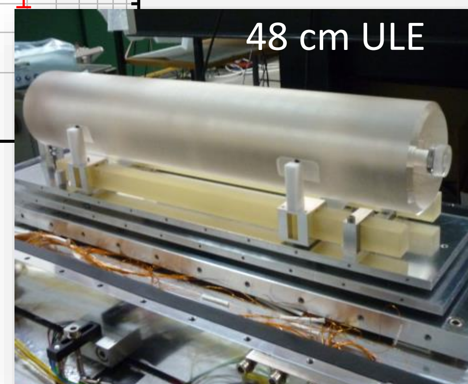

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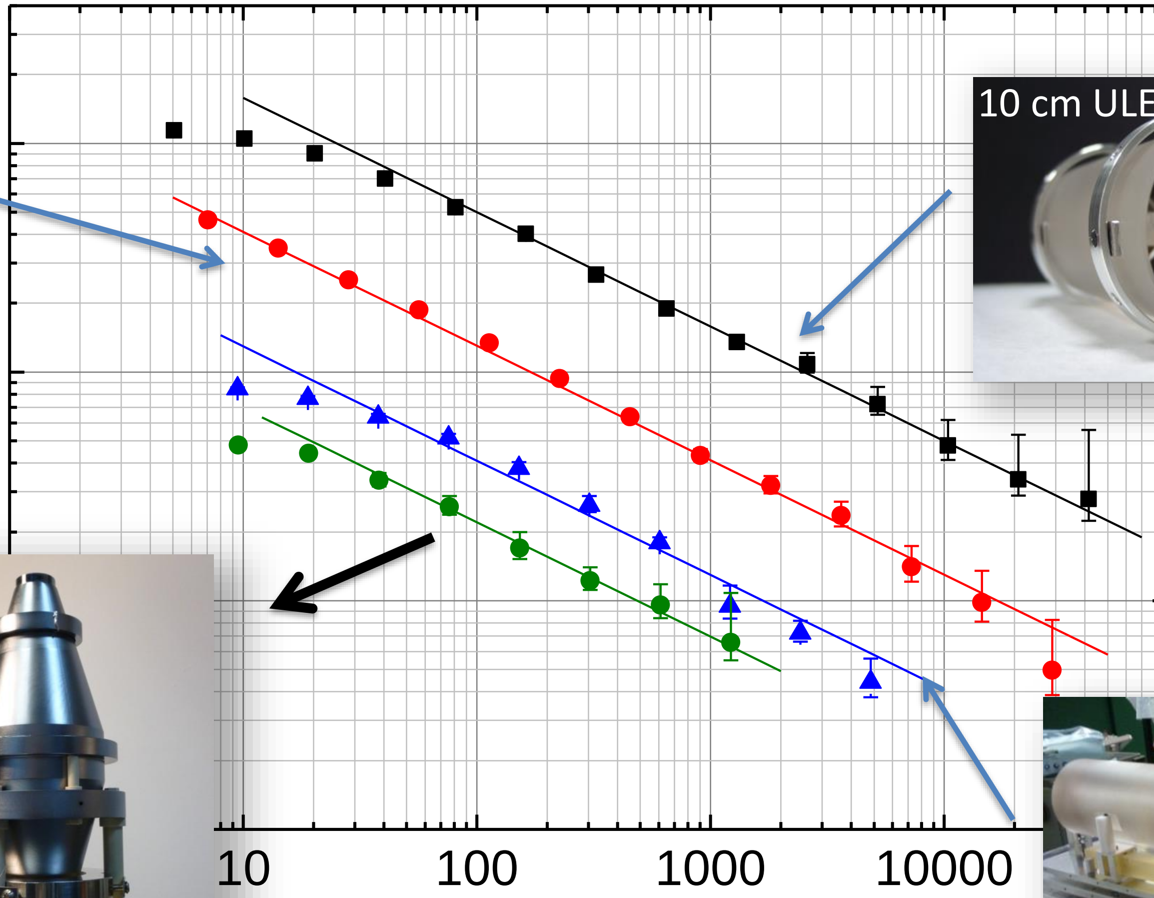
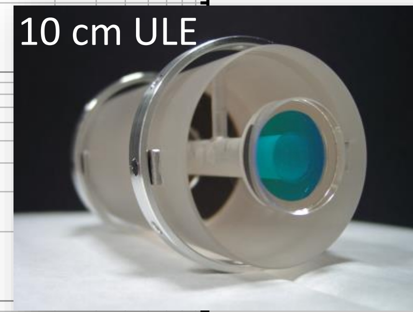
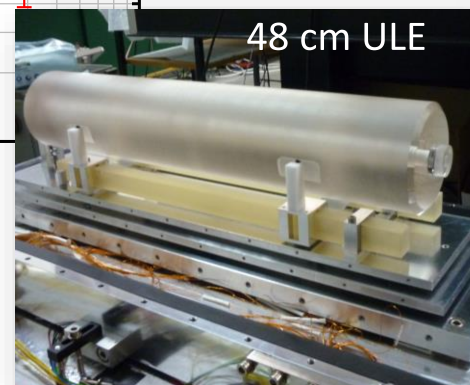






St. Falke e … 99 ,
Ch. Hagen … Meas. **62** (2013) 1556
A. Al-Masoudi *et al.*, PRA **92**, 063814 (2015)

Importance of the clock laser

FEM optimized cavity shape for minimal vibration sensitivity

expected thermal noise limit at T =123.5 K:

mod $\sigma_y \approx 4\times10^{-17}$

$$\frac{\Delta\nu}{\nu} = -\frac{\Delta L}{L}$$

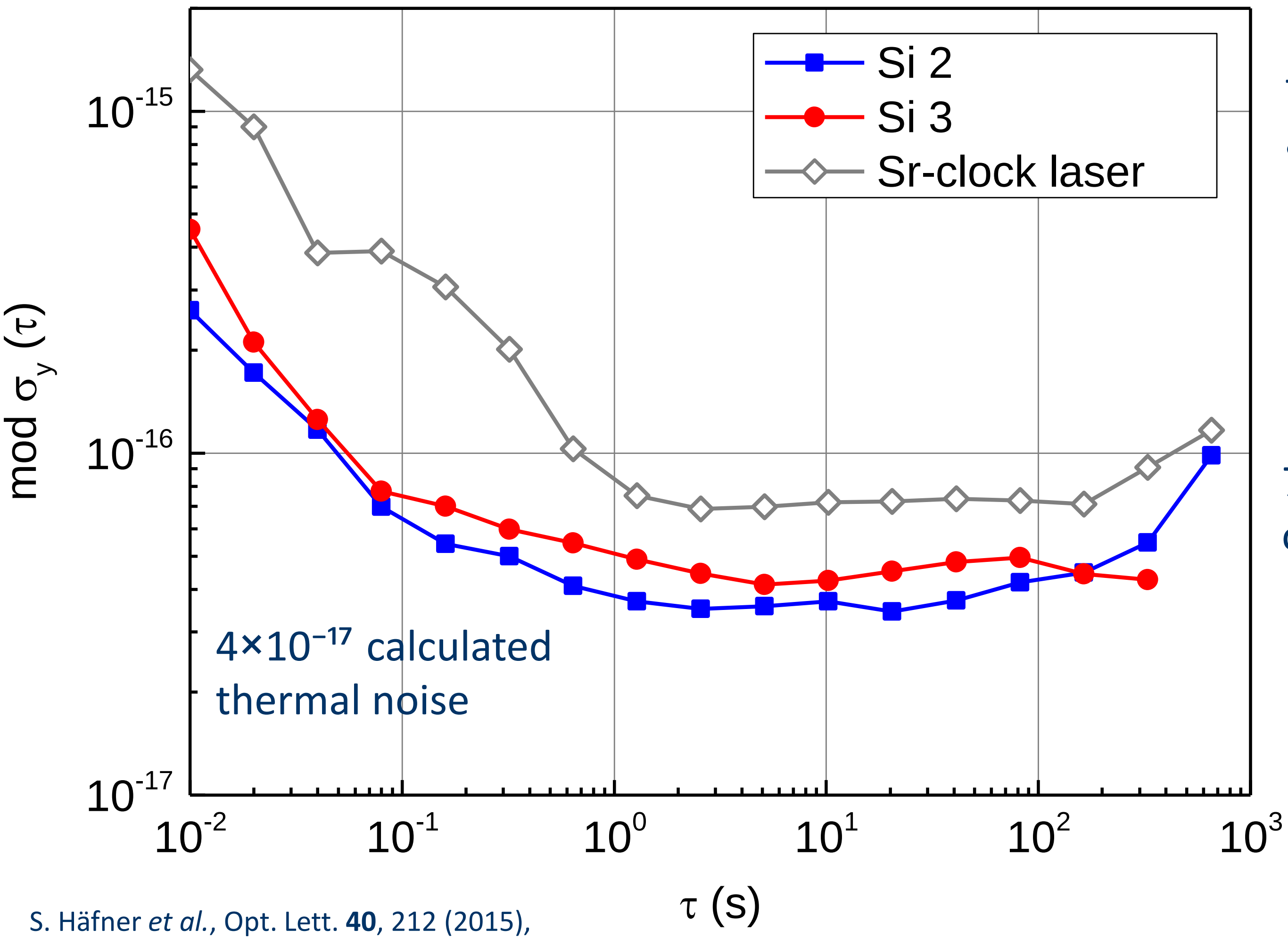
absolute length fluctuations $\approx 8.5\times10^{-18}$ m

dominated by mirror coatings!

proton diameter ≈ 0.85 fm = 850×10^{-18} m

T. Kessler *et al.*, Nature Phot. **6**, 687 (2012),
D. Matei *et al.*, Phys. Rev. Lett. **118**, 263202 (2017)

Importance of the clock laser



linear drift removed from Si 3 – Si 2 and Sr – Si 2 beats

7×10^{-17} thermal noise of ULE cavity

S. Häfner *et al.*, Opt. Lett. **40**, 212 (2015),
T. Kessler *et al.*, Nature Phot. **6**, 687 (2012),
D. Matei *et al.*, Phys. Rev. Lett. **118**, 263202 (2017)

Clock comparisons – local and non-local

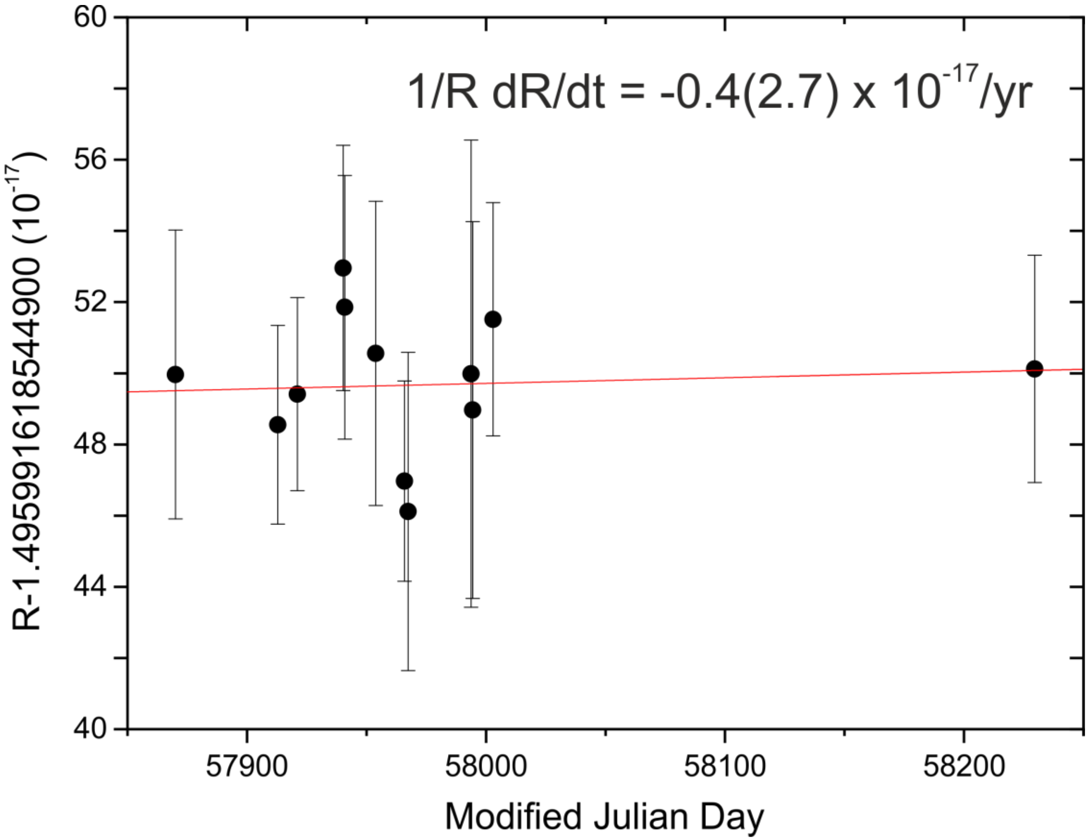
What can you do?

Yb^{+} single ion clock

building A building B

"Space Optical Sr Clock"

Clock comparisons – local and non-local



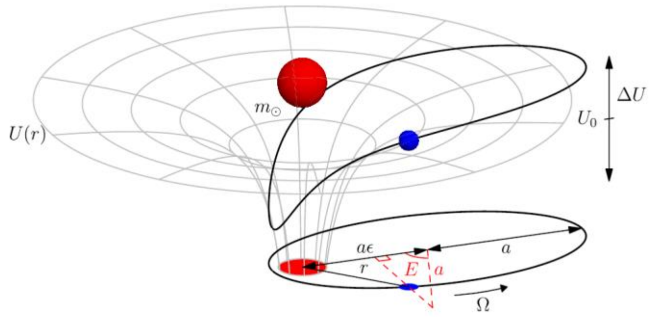
$$\mathcal{R} = \nu(\mathrm{Yb}^+, E3)/\nu(\mathrm{Sr})$$

$$\frac{\Delta\mathcal{R}}{\mathcal{R}} = -6\frac{\Delta\alpha}{\alpha}$$

- Yb^+/Sr frequency ratio magnifies α changes by 6
- Systematic uncertainty of the Sr clock 2×10^{-17}

C. Grebing et al., Optica **3**, 563 (2016).
N. Huntemann et al., PRL **113**, 210802 (2014)

Repeated comparisons – interpretation

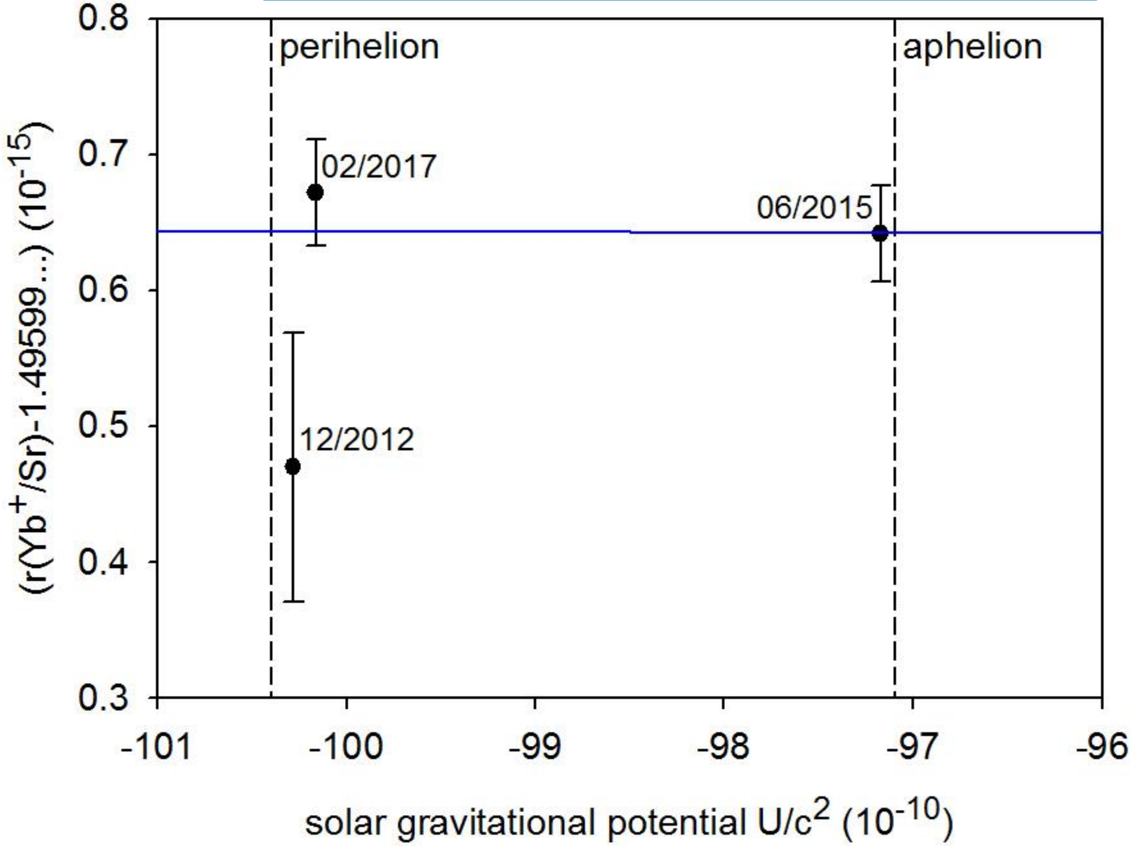


from: S. Blatt et al., Phys. Rev. Lett. **100**, 140801 (2008)

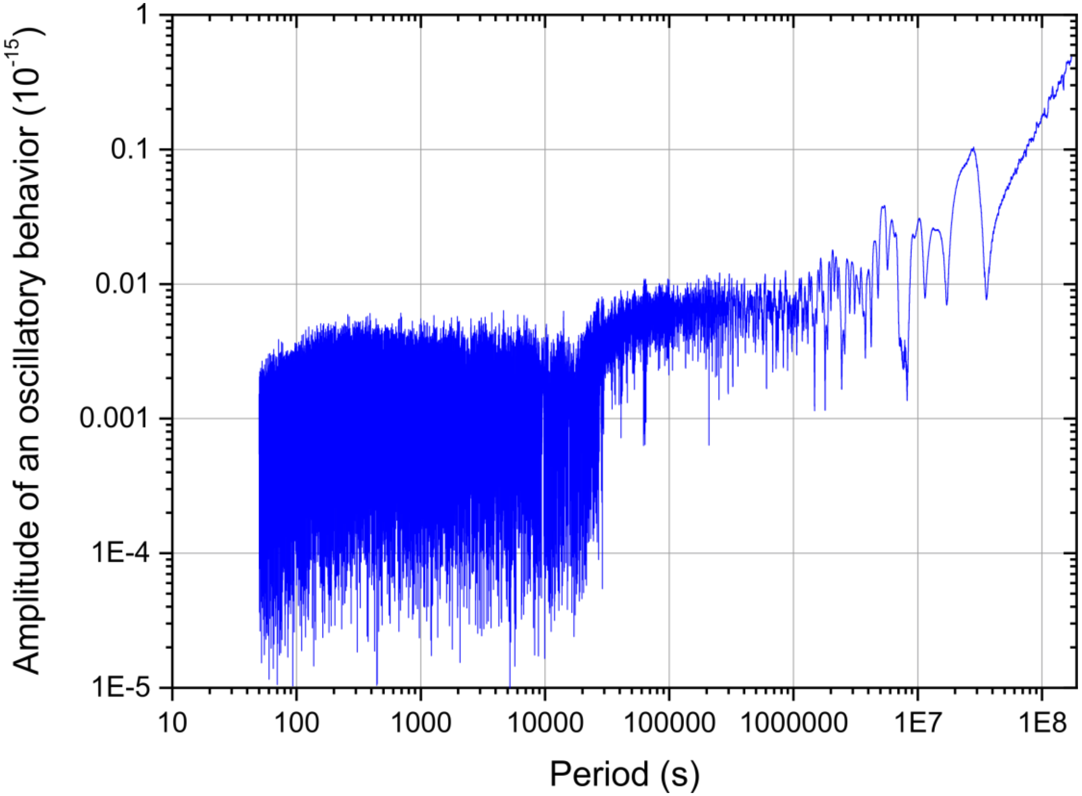
$(c^2/\alpha)\, d\alpha/dU = 2.5(3.1)\times10^{-6}$

S. Blatt et al., Phys. Rev. Lett. **100**, 140801 (2008)

$(c^2/\alpha)\, d\alpha/dU = 0.1(1.9)\times10^{-8}$



Clock comparisons – local and non-local



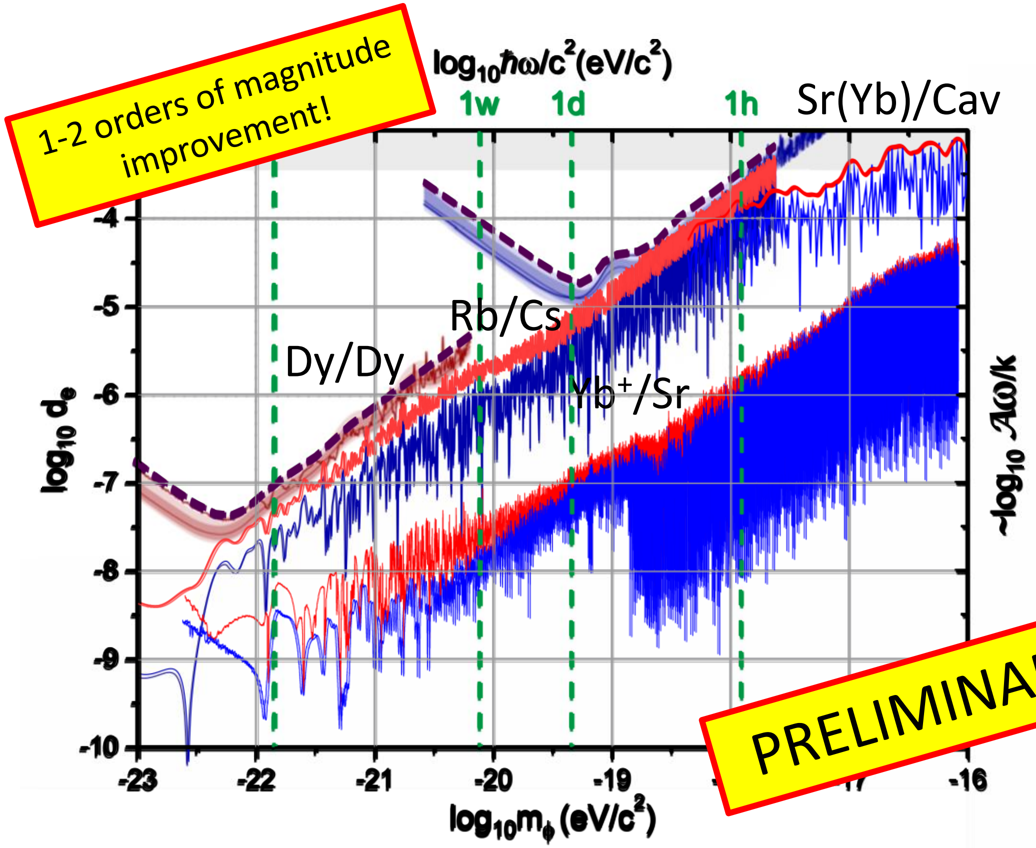
$$\mathcal{R} = \nu(\mathrm{Yb}^+, E3)/\nu(\mathrm{Sr})$$

$$\frac{\Delta\mathcal{R}}{\mathcal{R}} = -6\frac{\Delta\alpha}{\alpha}$$

- Yb^+/Sr frequency ratio magnifies α changes by 6
- Systematic uncertainty of the Sr clocks 2×10^{-17}
- No oscillatory behaviour of the frequency ratio
- More than 24 days of data

C. Grebing et al., Optica **3**, 563 (2016).
N. Huntemann et al., PRL **113**, 210802 (2014)

Clock comparisons – local and non-local



Hypothetical coupling of dark matter to the electromagnetic field tensor leads to an oscillation in α and in turn in $\mathcal{R}$ with an amplitude:

$$\mathcal{A} = k_\alpha d_e \frac{1}{\omega} \left(\frac{8\pi G}{c^2} \rho_{\mathrm{DM}} \right)^{1/2},$$

$$\rho_{\mathrm{DM}} \approx 0.4\, \frac{\mathrm{GeV}}{\mathrm{cm}^3}$$

Ratio measurements provide limits on d_e.

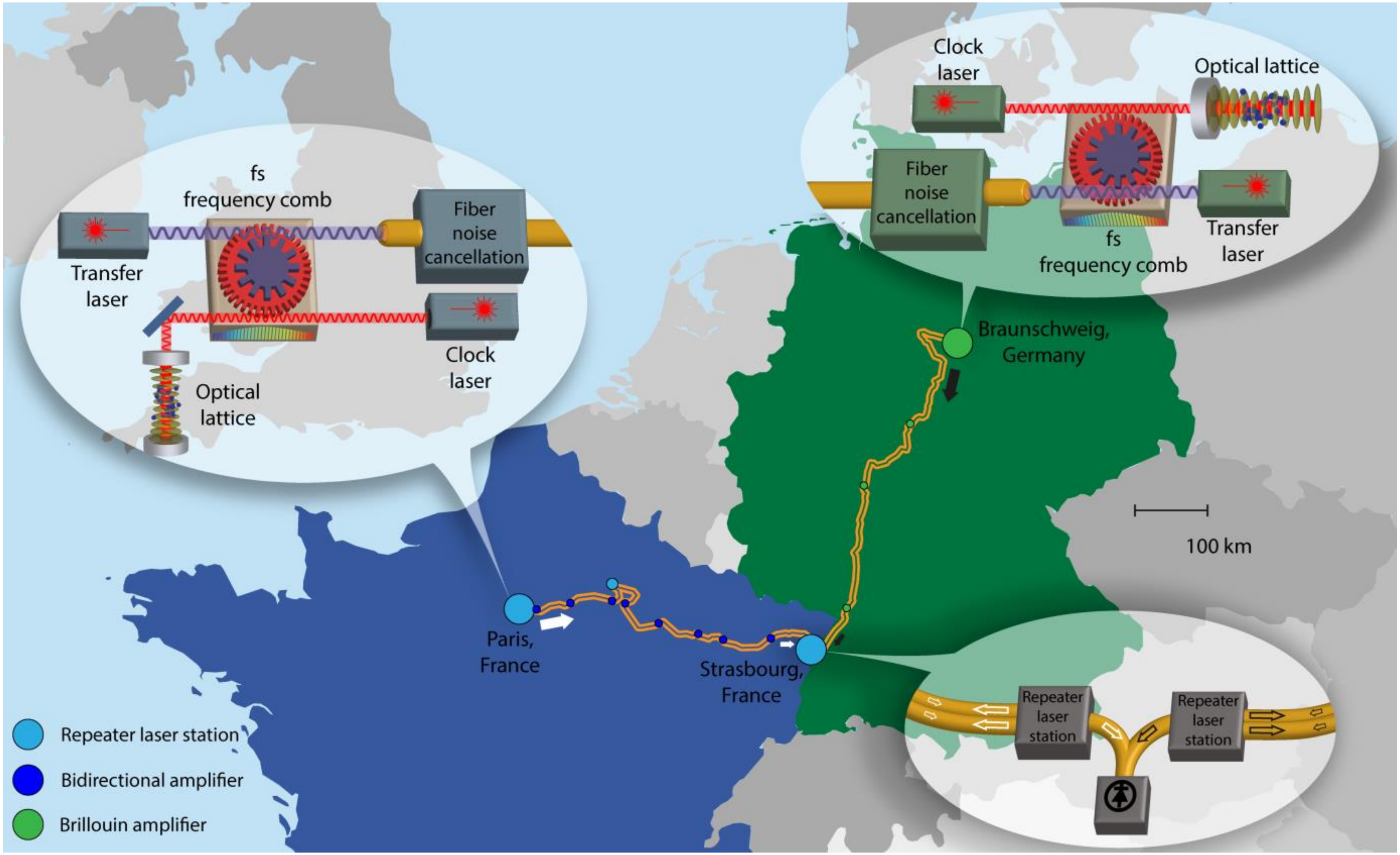
A. Arvanitaki et al., PRD 91, 015015 (2015)

Dy/Dy: K. Van Tilburg et al., PRL **115**, 011802 (2015)

Rb/Cs: A. Hees et al., PRL **117**, 061301 (2016)

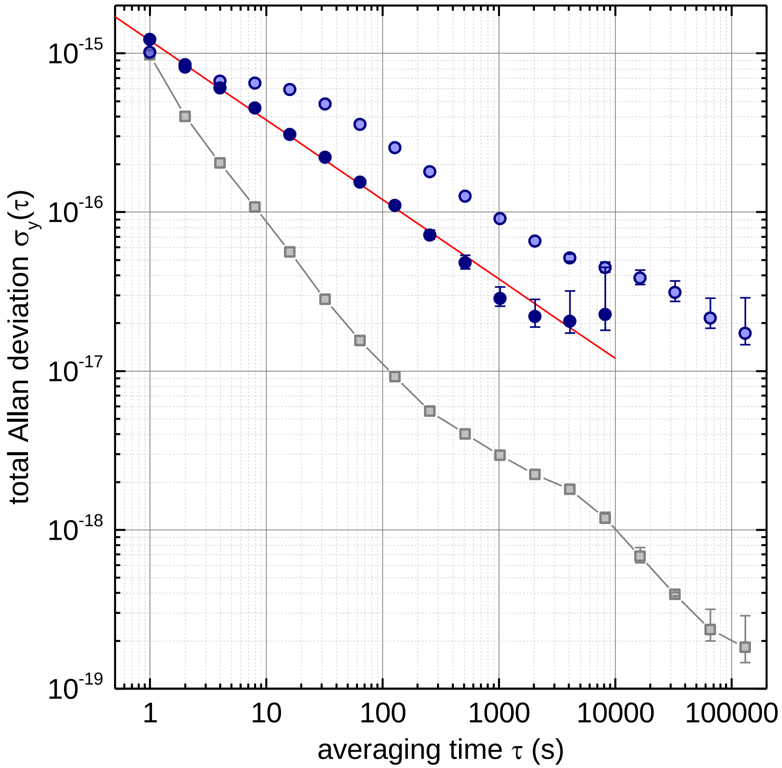
Sr(Yb)/Cav: P. Wcislo et al., arXiv:180604762 (2018)

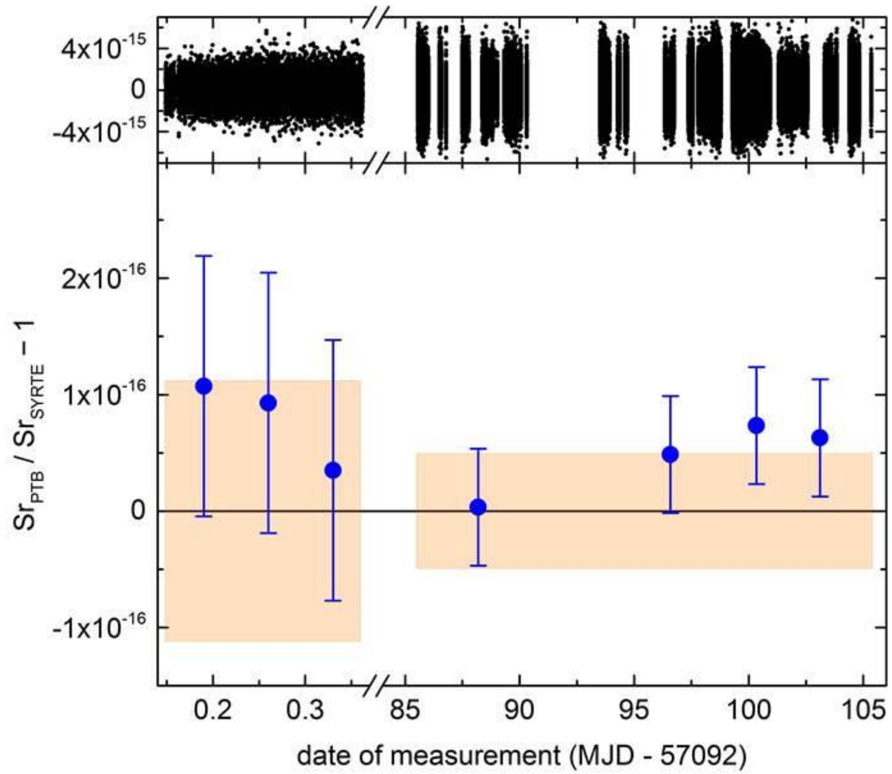
Clock comparisons – local and non-local



Ch. Lisdat *et al.*, Nature Comms. **7**, 12443 (2016)

Clock comparisons – Paris & Braunschweig



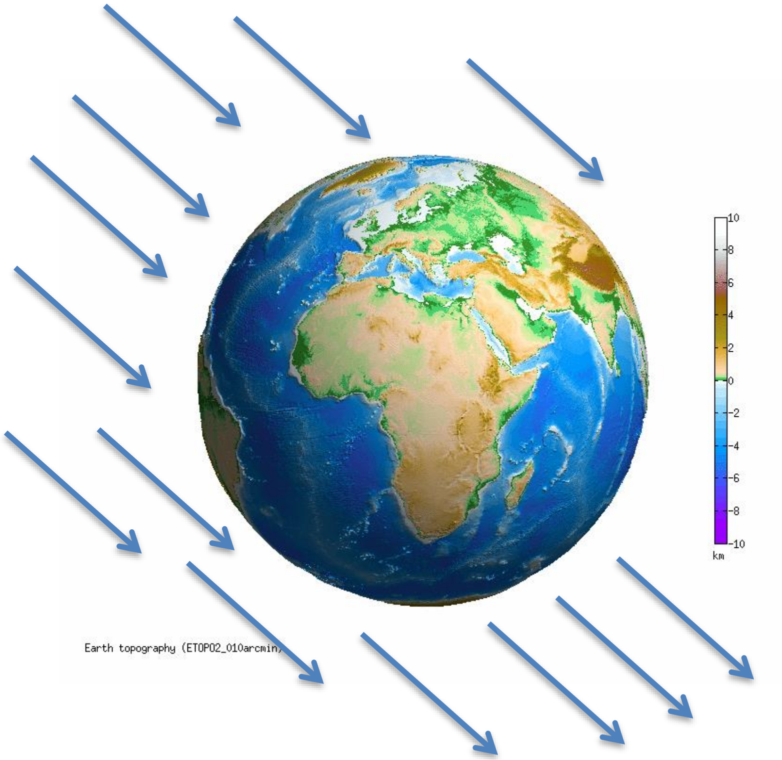


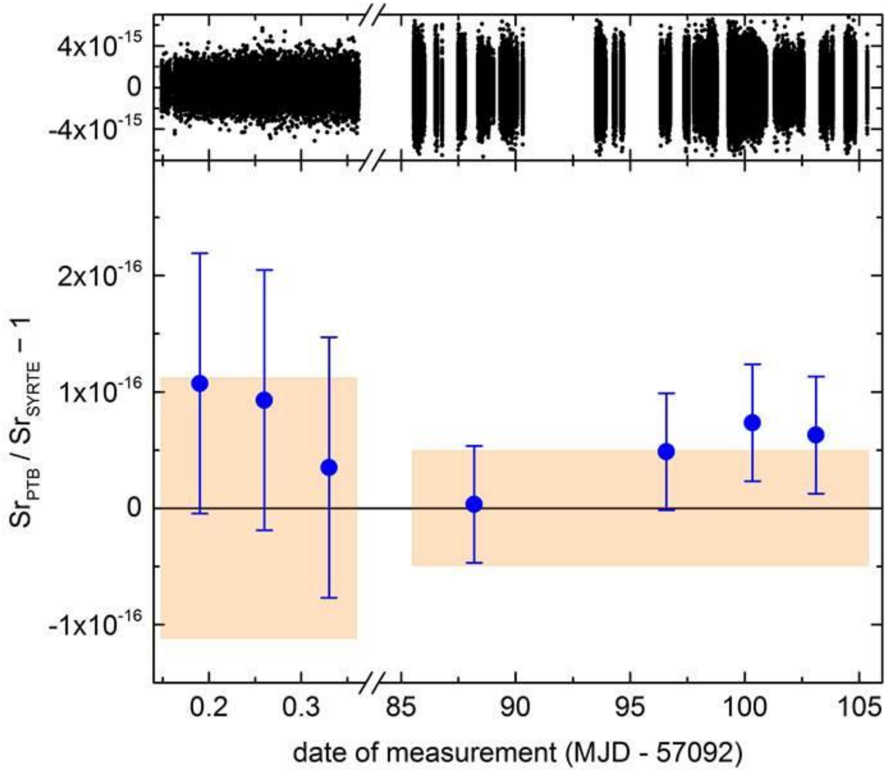
Gravity potential correction
$-247.2(4)\times10^{-17}$

Ch. Lisdat *et al.*, Nature Comms. **7**, 12443 (2016)

Clock comparisons – Paris & Braunschweig

Local Lorentz invariance: search for daily modulation due to motion wrt. background





animation: A. Bezdek and J. Sebera, Computers & Geosciences **56**, 127 (2013), data set: ETOPO2 / EGM2008

Clock comparisons – Paris & Braunschweig

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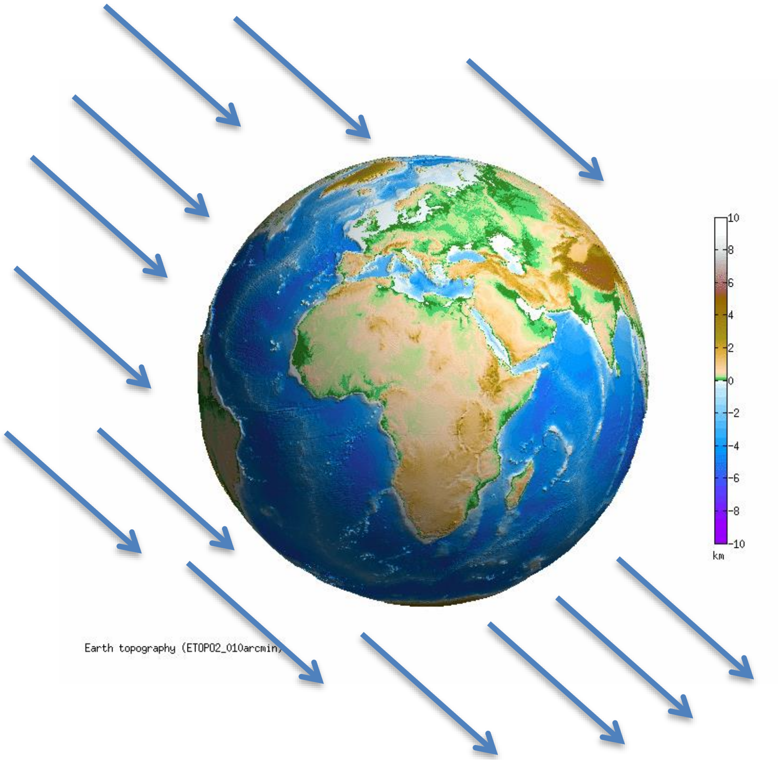


was done with Rb clocks (GPS)
P. Wolf & G. Petit, Phys. Rev. A **56**, 4405 (1997)

$|\alpha| \leq 10^{-6}$

LLI test also with fast ion beams
B. Botermann *et al.*, Phys. Rev. Lett. **113**, 120405 (2014)

$|\alpha| \leq 2 \times 10^{-8}$

Sr clocks London, Paris, Braunschweig
P. Delva *et al.*, Phys. Rev. Lett. **118**, 221102 (2017)

$|\alpha| \leq 1.2 \times 10^{-8}$

animation: A. Bezdek and J. Sebera, Computers & Geosciences **56**, 127 (2013), data set: ETOPO2 / EGM2008

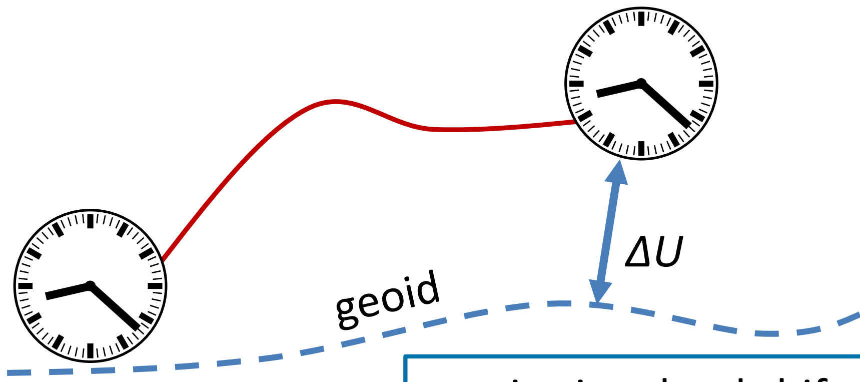
Transportable optical clocks

Leaving the lab:
Transportable clocks

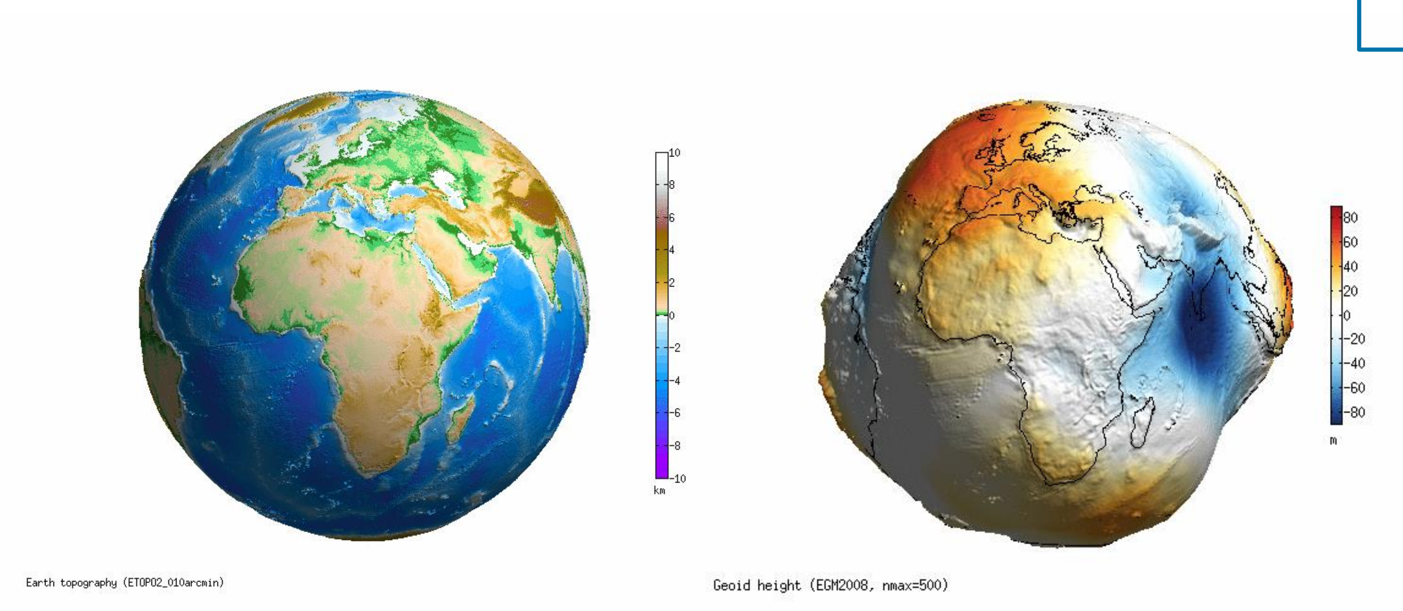
- flexibility of clock pairs
- choose operation sites
  to probe the gravity potential
- first step towards space

Transportable optical clocks

- Optical clocks as sensors:
  - Directly measure potential differences.
  - Vision: Realize geoid by clocks.



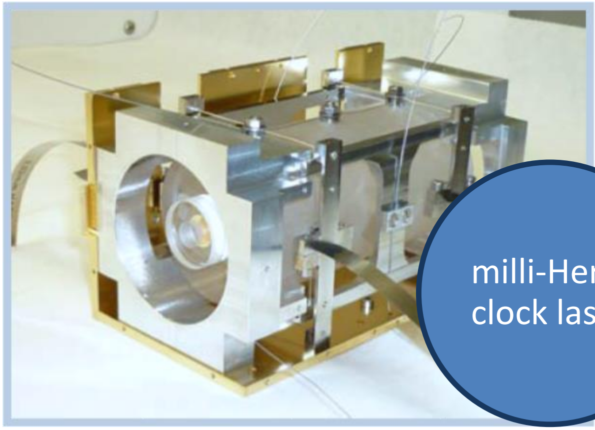
gravitational red shift:
$\Delta\nu/\nu = \Delta U/c^2$



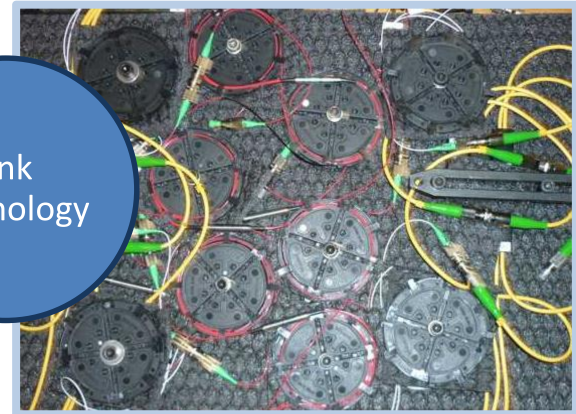
M. Vermeer, Rep. of the Finnish Geod. Insti. **83**, 1 (1983)

A. Bjerhammar, Bull. Geodesique **59**, 207 (1985)

Transportable optical clocks

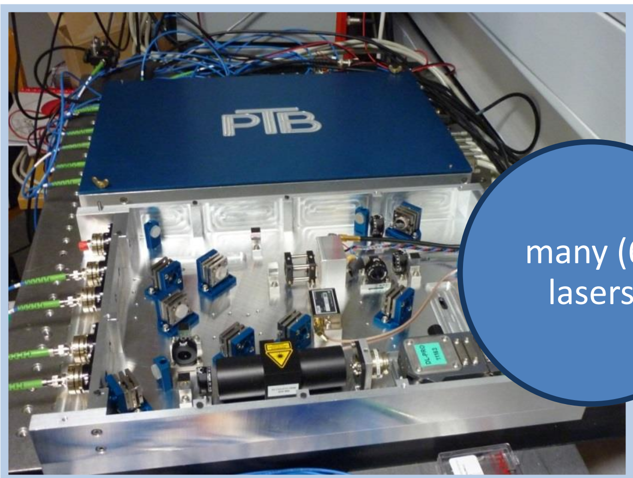


milli-Hertz clock laser



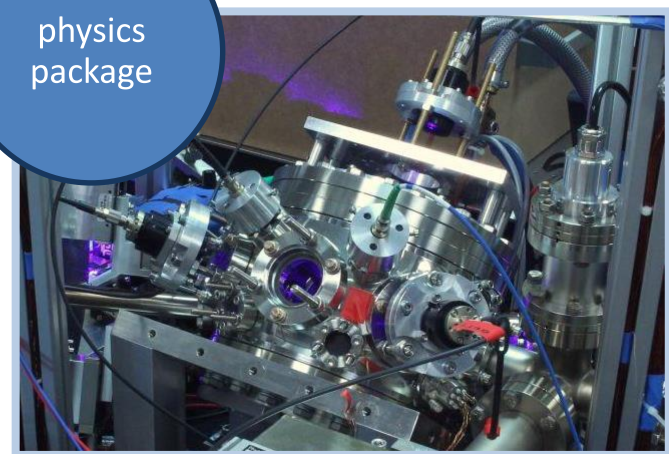
link technology

Sr



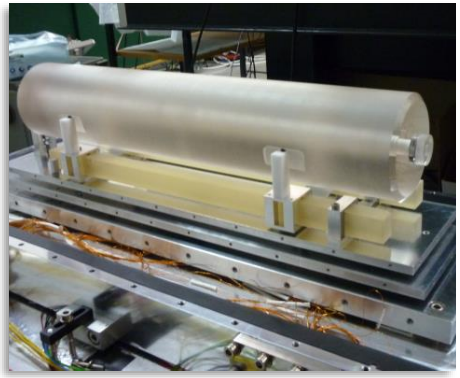
many (6) lasers

physics package



Importance of the clock laser

Clock lasers in labs:

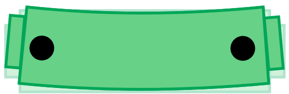


48 cm ULE cavity

cryogenic 21 cm silicon cavity

S. Häfner *et al.*, Opt. Lett. **40**, 212 (2015),
D. Matei *et al.*, Phys. Rev. Lett. **118**, 263202 (2017)

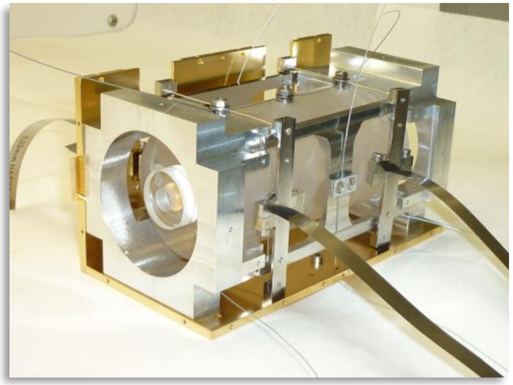
acceleration sensitivity



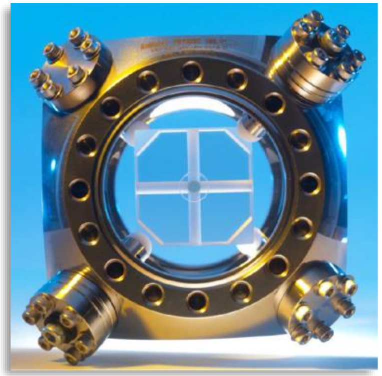
⇕

thermal noise

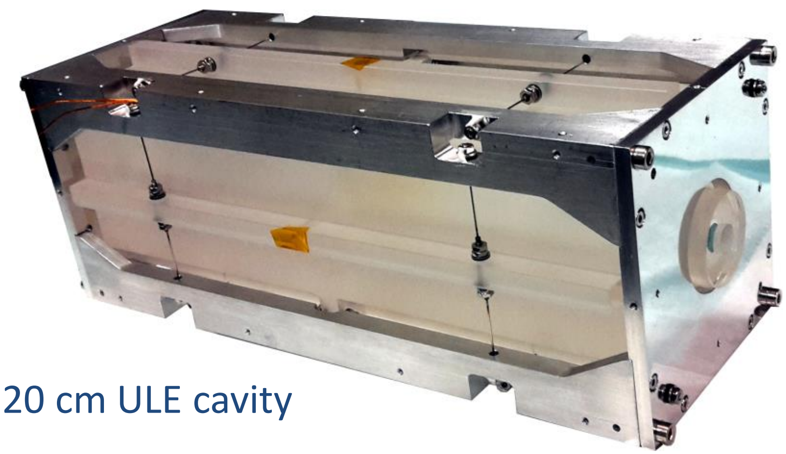
Transportable clock lasers:



12 cm ULE cavity



5 cm ULE cavity



20 cm ULE cavity

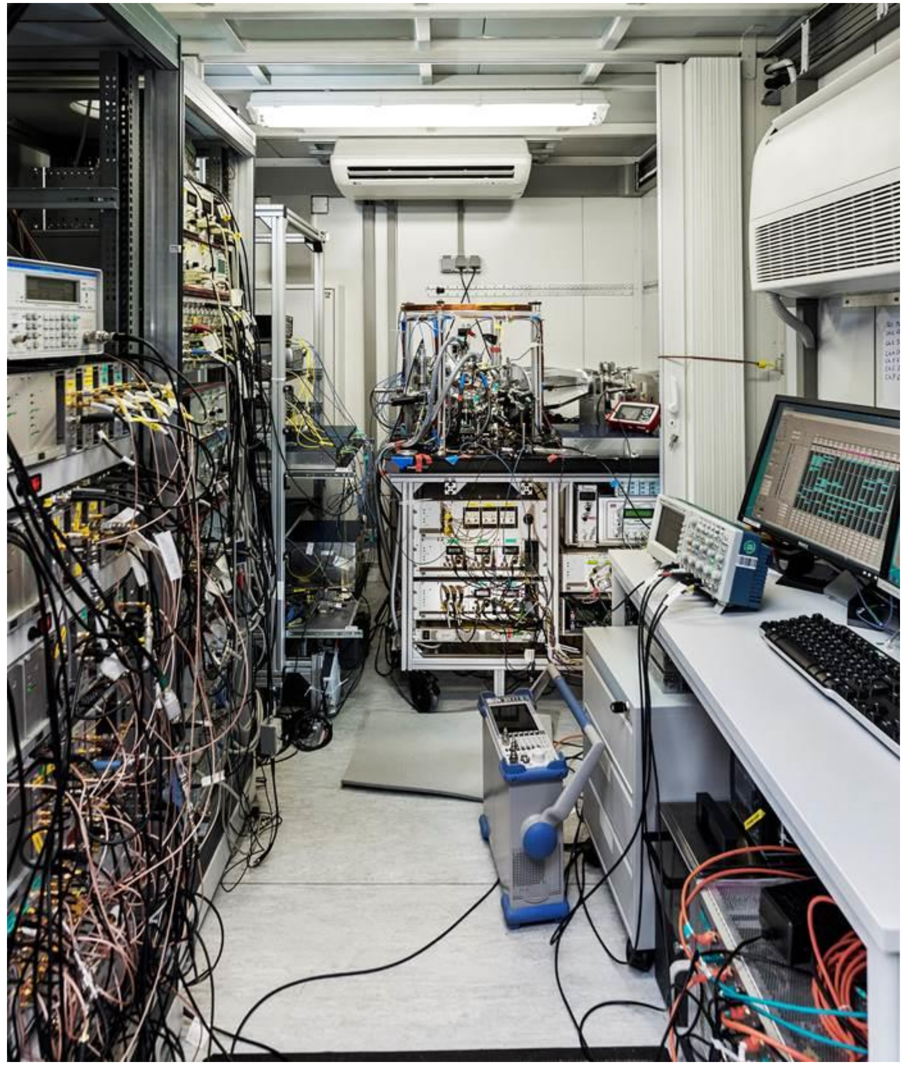
S. Koller *et al.*, Phys. Rev. Lett. **118**, 073601 (2017)
S. Webster & P. Gill, Opt. Lett. **36**, 3572 (2011)

Transportable optical clocks

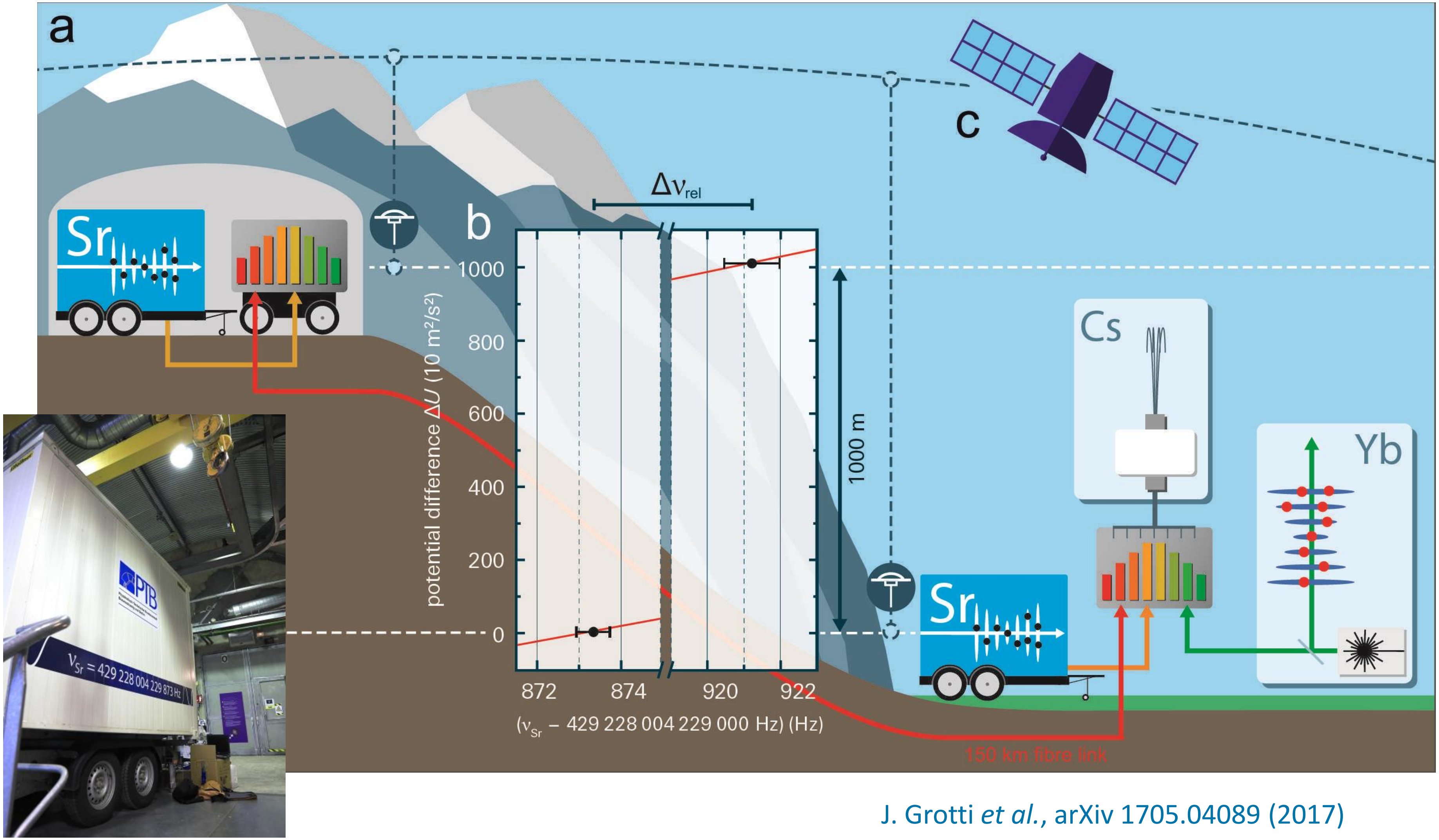
Car trailer housing the clock

S. Koller *et al.*, Phys. Rev. Lett. **118**, 073601 (2017)

View into the car trailer ▶

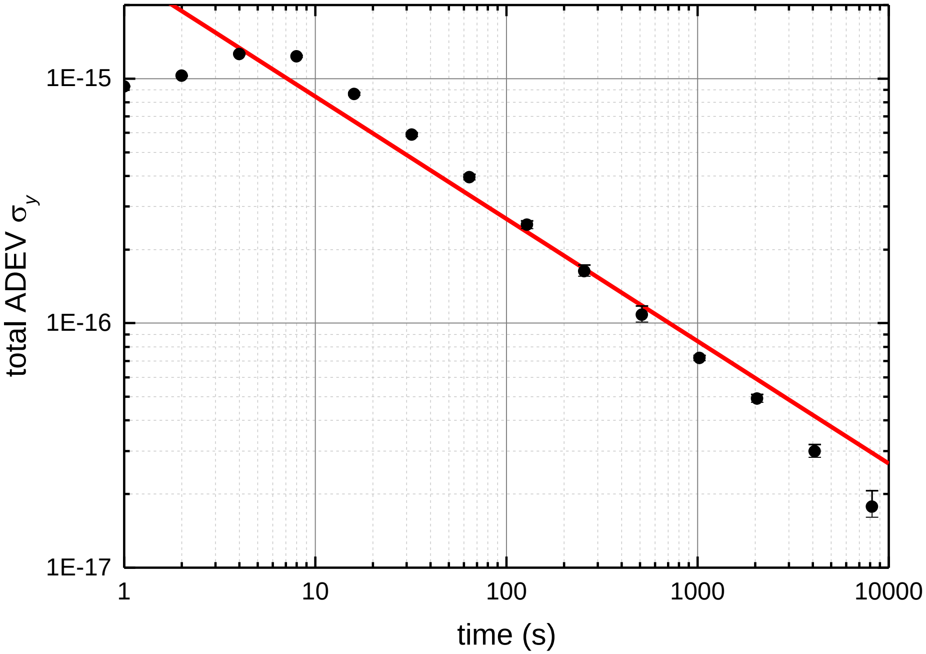


First time off-campus: Modane – Torino 2016



J. Grotti *et al.*, arXiv 1705.04089 (2017)

Second campaign: Paris – Braunschweig 2017



Combined uncertainty ≈ 3×10^{-17} or 30 cm in 3 hours.

Gravity potential correction from geodesy: $-247.2(4)\times10^{-17}$

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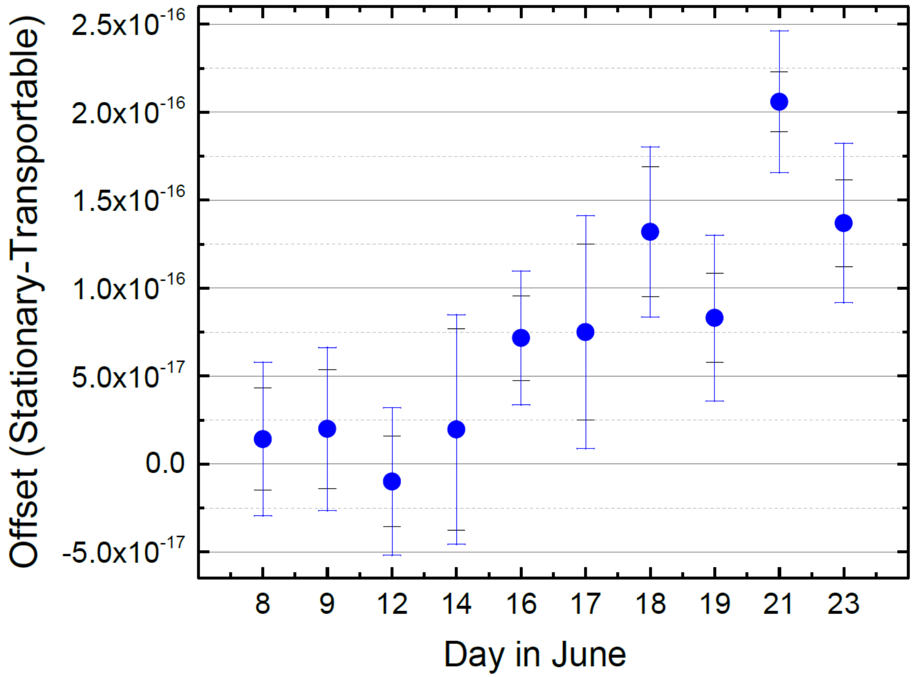
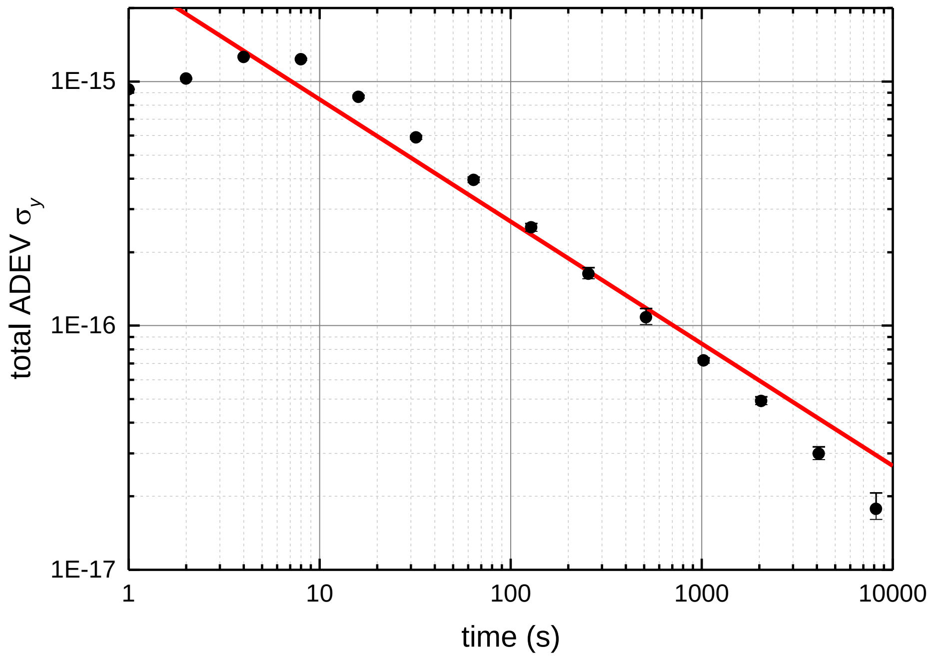




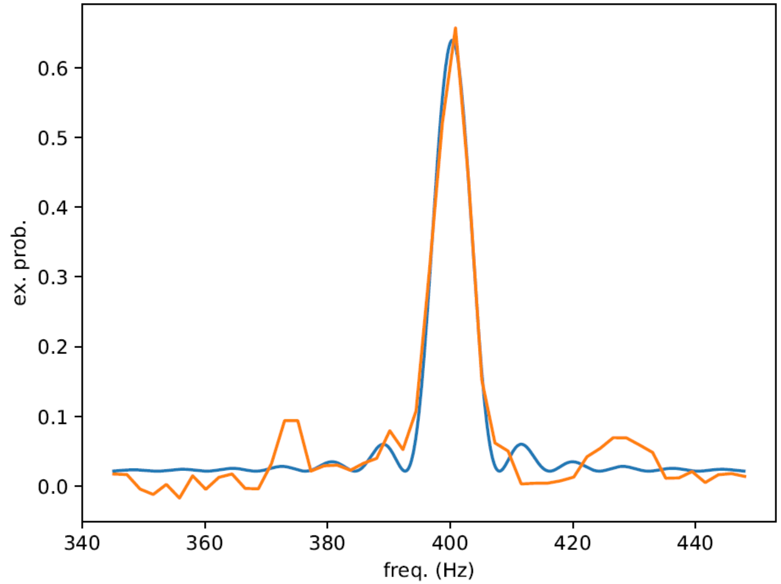
Combined uncertainty ≈ 3×10^{-17} or 30 cm in 3 hours.

Gravity potential correction from geodesy: $-247.2(4)\times10^{-17}$

unfortunately: 'anomaly' in the second half of the campaign

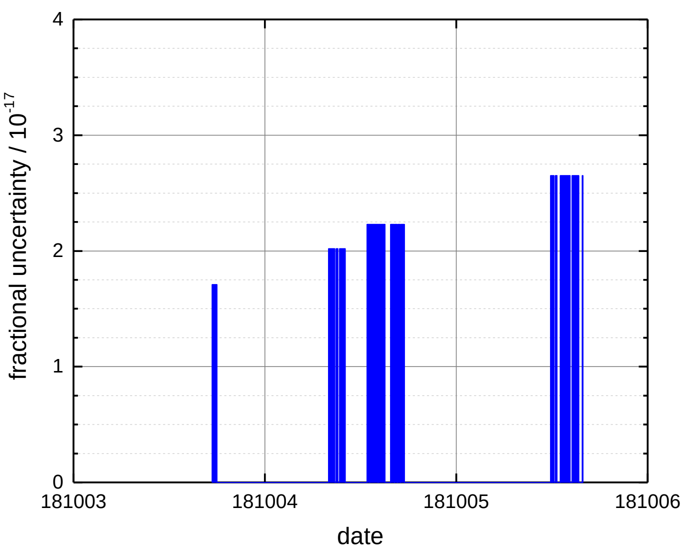
Third campaign: Munich – Braunschweig 2018

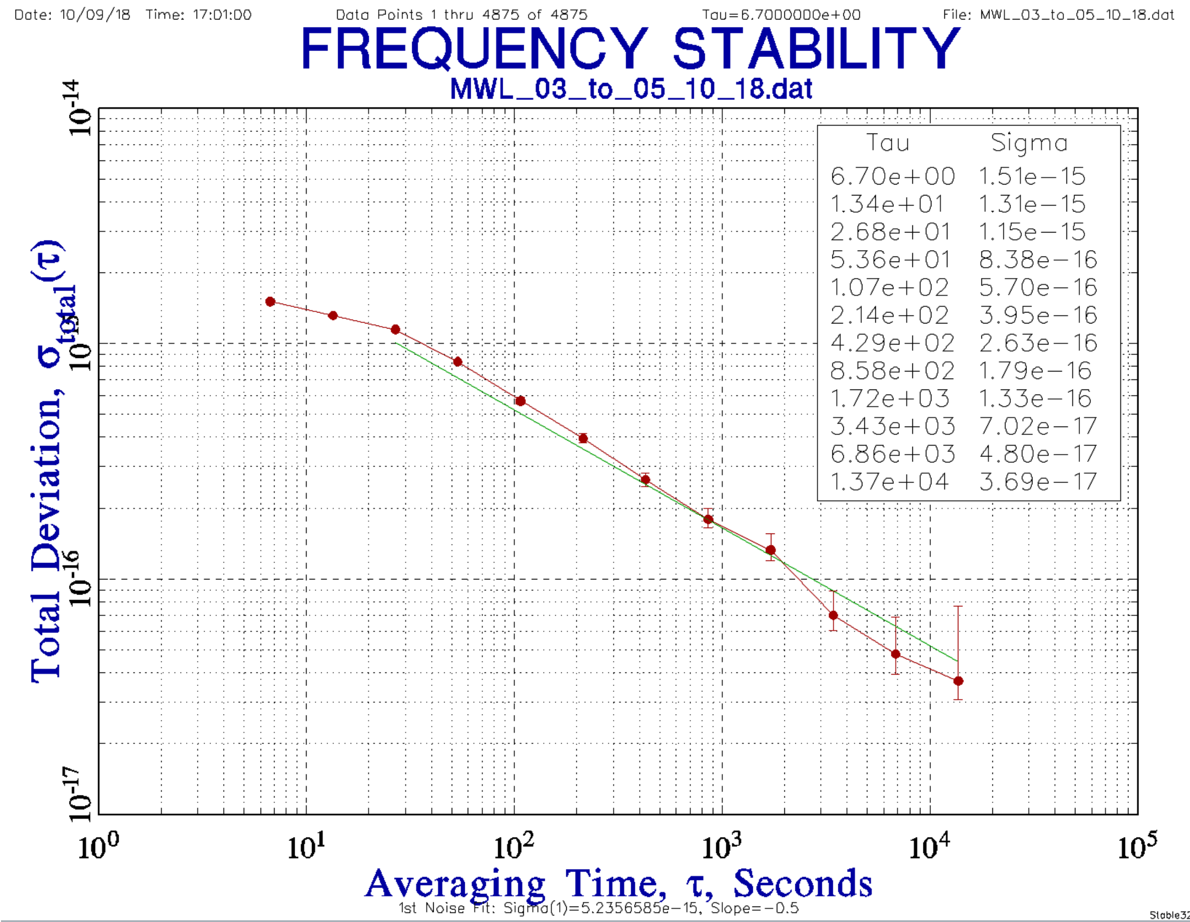
- Need for further practise and improvements
- 5 days after arrival: atoms in the lattice
- second week: problems with spectroscopy
  perturbation of the clock laser



Third campaign: Munich – Braunschweig 2018

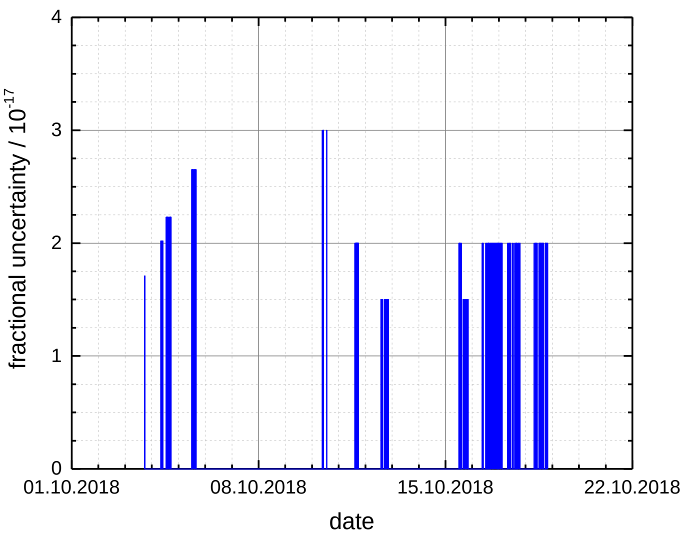
- Third week: Clock laser sidebands removed (fibre between clock laser and cavity)
- instability: $5\times10^{-15}\,\tau^{-1/2}$

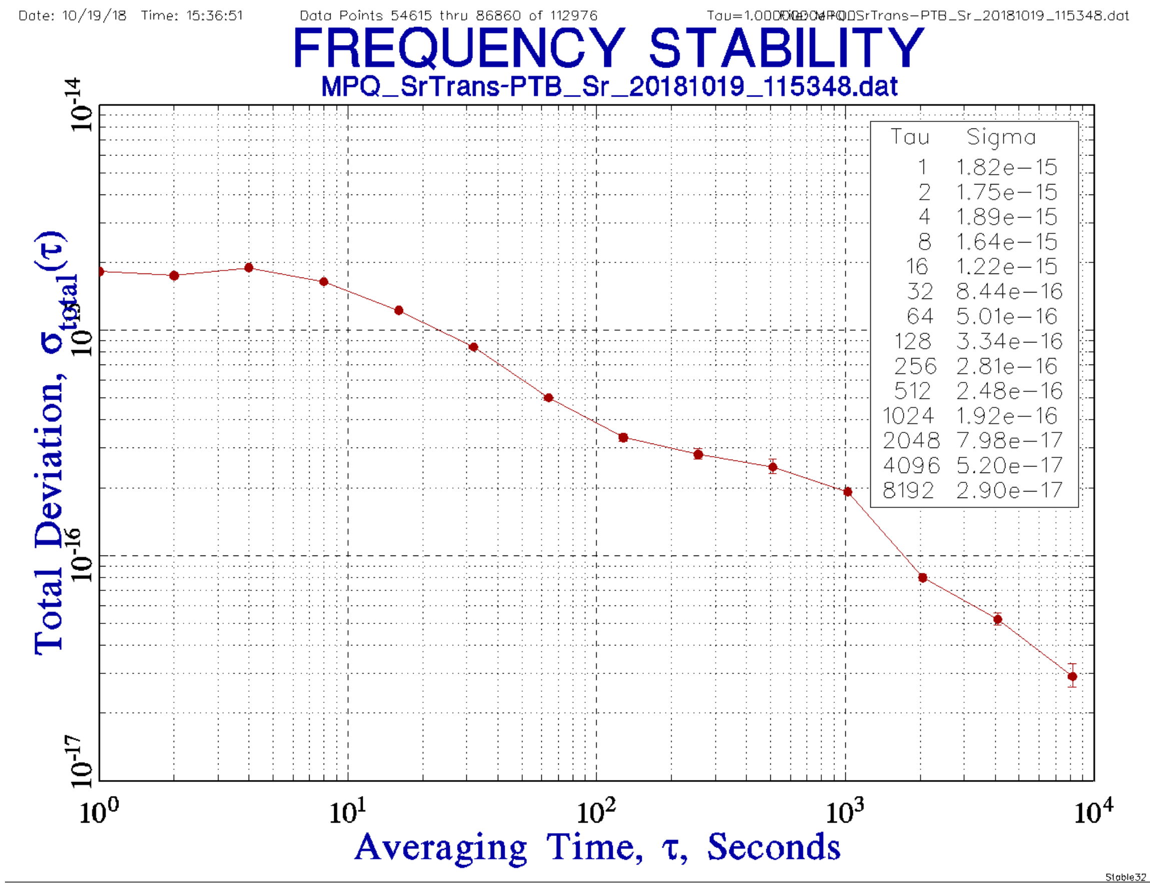




Third campaign: Munich – Braunschweig 2018

- improved counting of clock laser by the comb (week 4)
- more data … (week 5)





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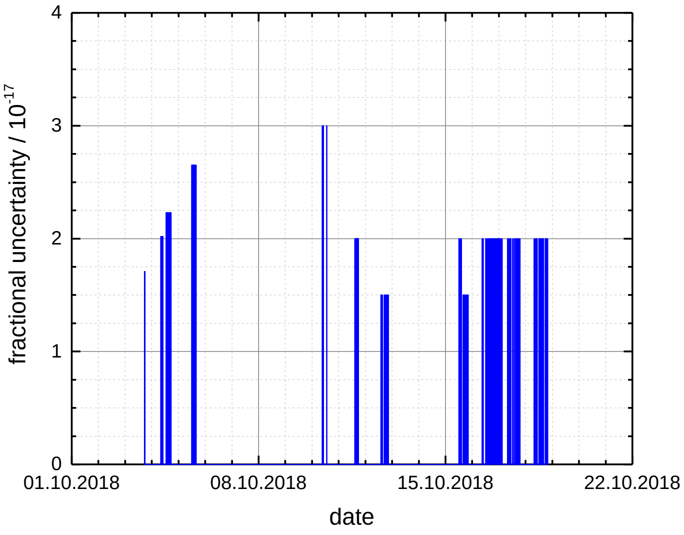

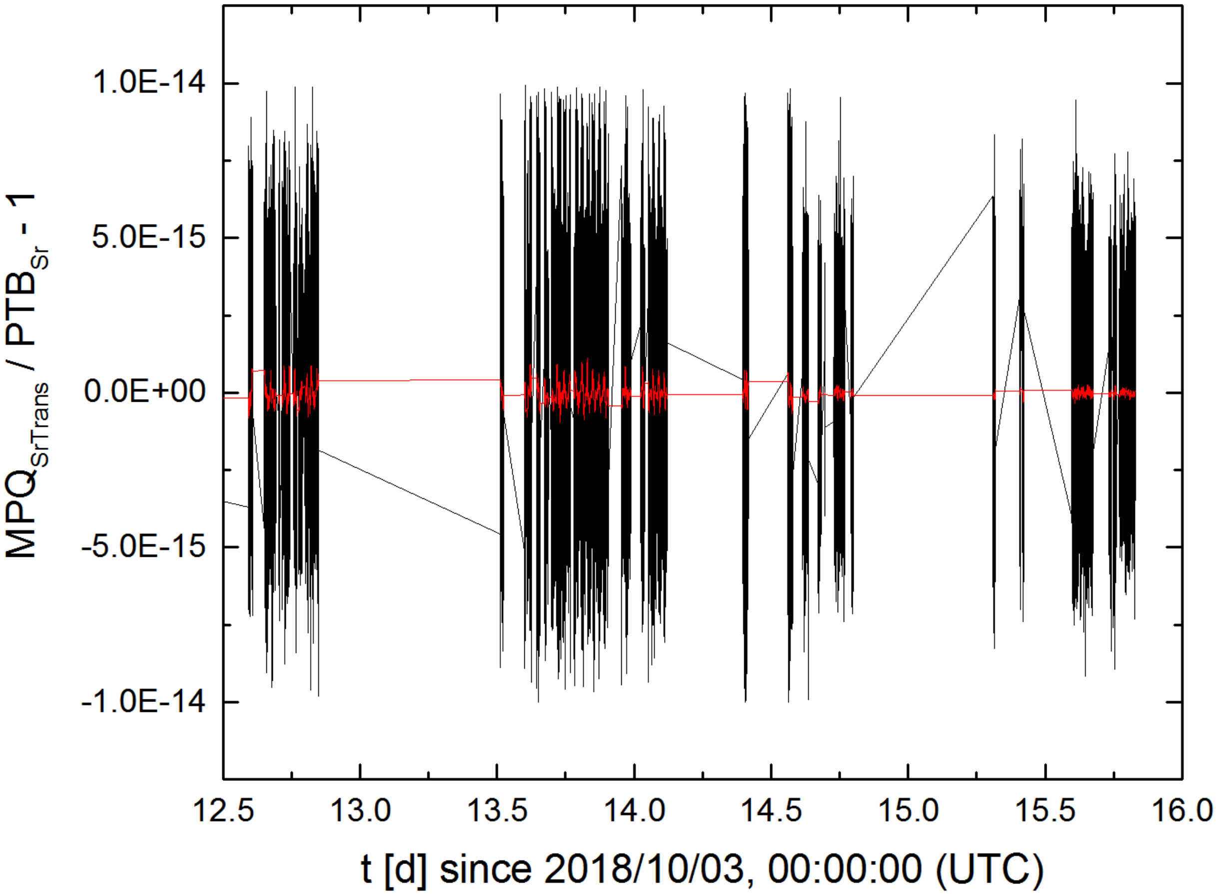

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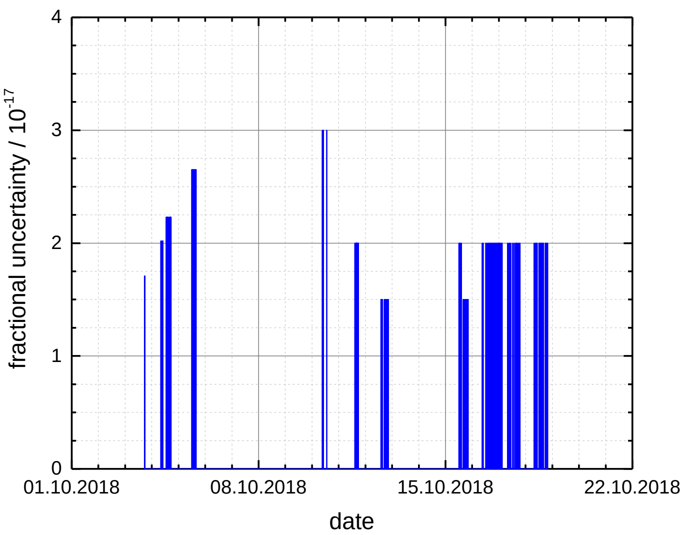

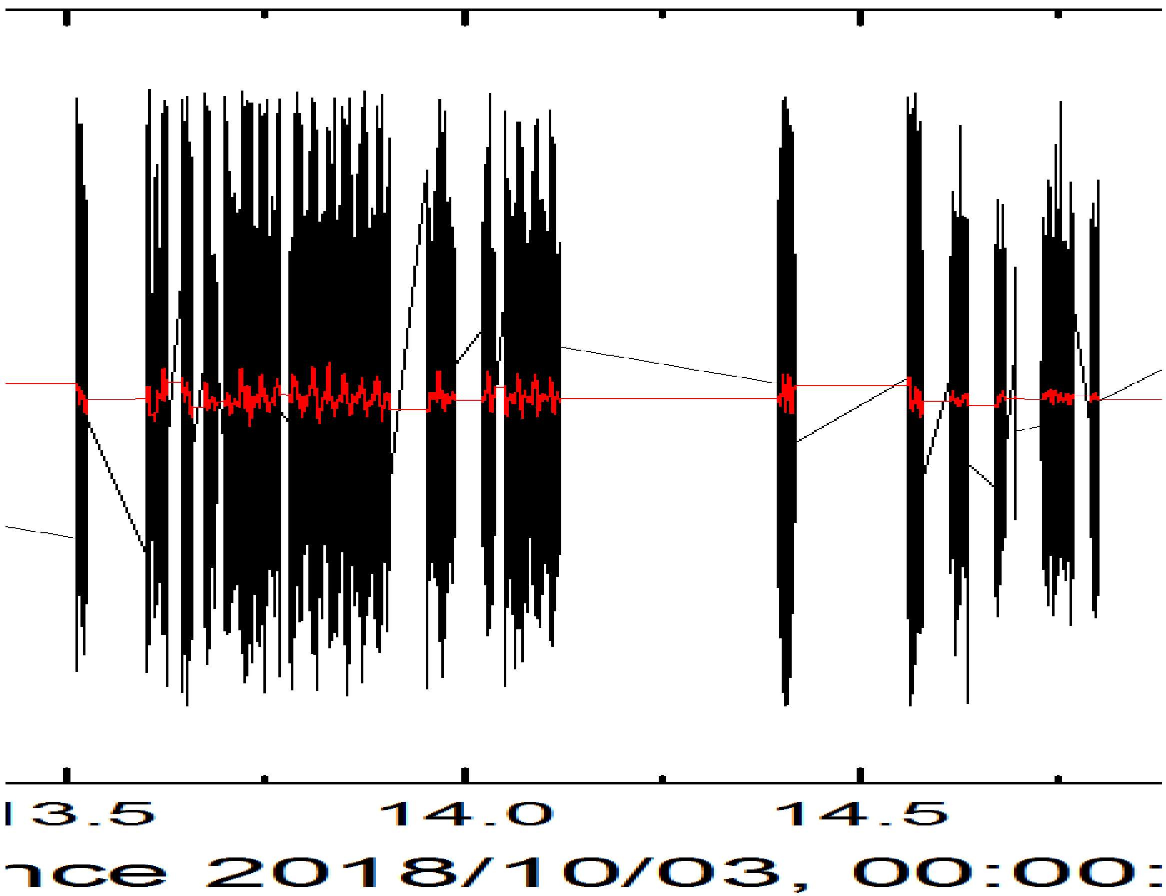

In conclusion:

- There is always something new …
- Reliability is still an issue
  procedures for ‘quality management’ have to be improved
  hardware improvements are ongoing
- I still think that we can do this, even in space!
- 10^{-17} or 10 cm now, 10^{-18} or 1 cm in a few years

Many thanks to:

Strontium:

J. Grotti
S. Koller
S. Herbers
S. Vogt
S. Dörscher
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R. Schwarz

& people who want to join us

Cavities & Combs:

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E. Benkler
D. Matei
T. Legero
U. Sterr

Yb^{+} group at PTB

Fibre link group at PTB

Teams in NMIs

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France (SYRTE)
Teddington (NPL)

MPQ team at Munich

SOC team

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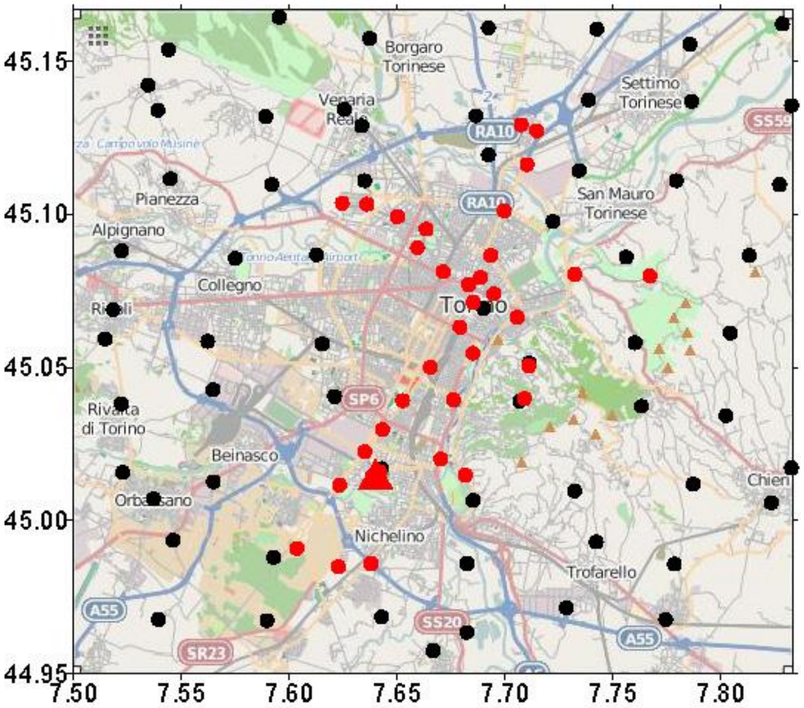
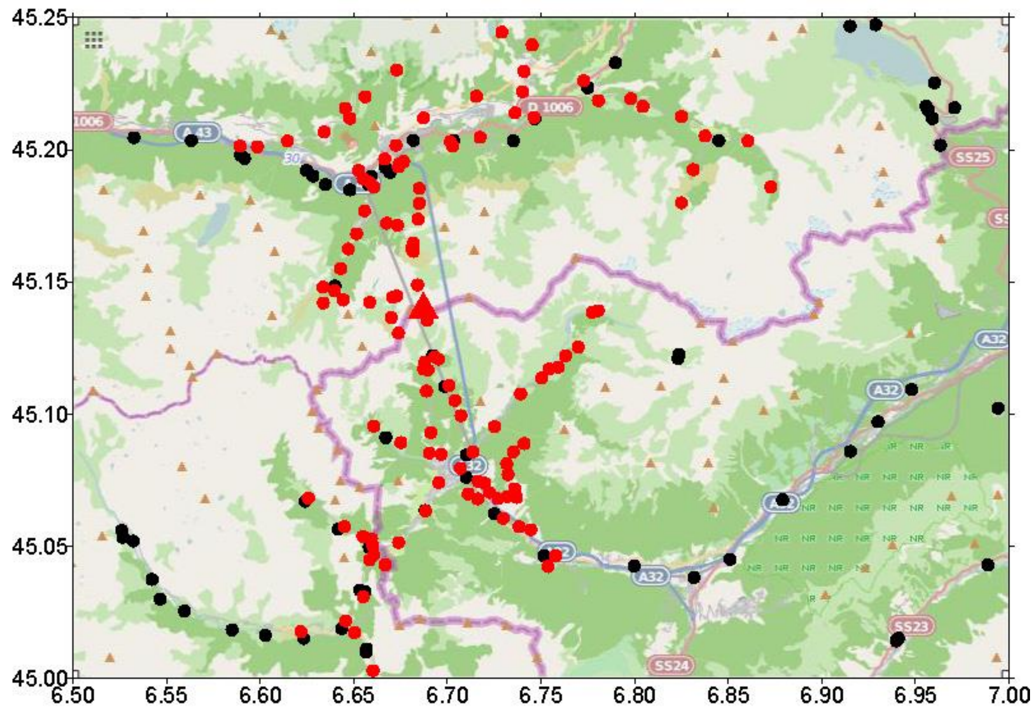
Stand: 02/17

Status PTB's transportable lattice clock

- ► Approaching design uncertainty of 1×10^{-17}
- ► Reliability is still a problem
  – but it is obvious that you can do better
- ► Balance design/construction effort with salary of PhD student
- ► Next generation: lower uncertainty (1×10^{-18}?)
  more 'user friendly'
  as heavy and power hungry

Gravity measurements Modane/Torino





© OpenStreetmap

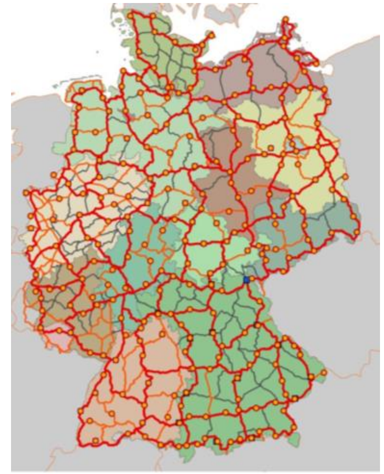
Bedeutung transportabler Uhren

Erdbeobachtung:

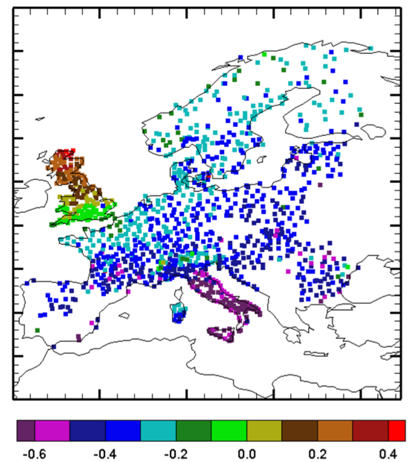
- Nivellement
  - kleinschrittig (60 m)
  - Fehlerakkumulation
- Schwerefeldmessung (Geoid) & GNSS
  - Satellitendaten
  - niedrige Ortsauflösung

3 cm Höhenauflösung über 500 km

≙ 3×10^{-18} Uhrengenauigkeit



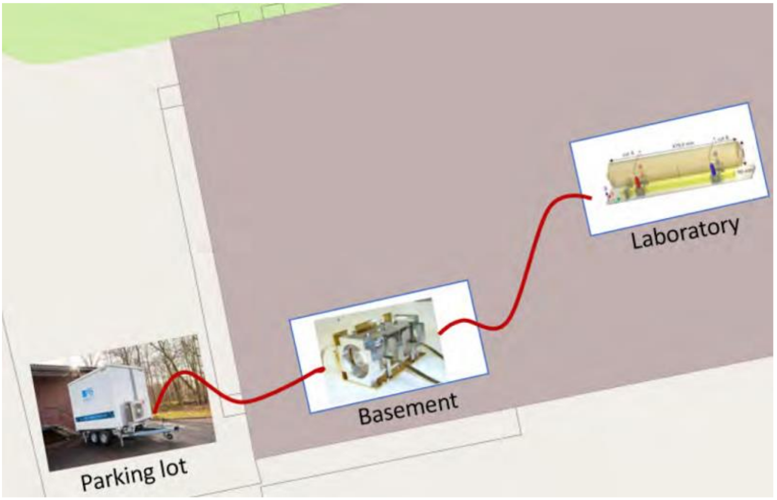
source: BKG/IfE

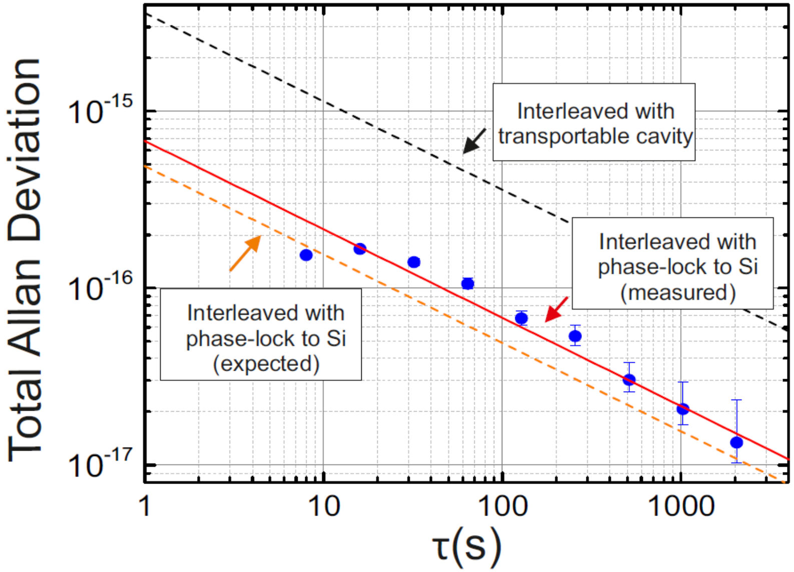


Leveled heights – GNSS/geoid heights (m)

Gruber et al., ESA report GO-HSU-PL-0021
Height System Unification with GOCE

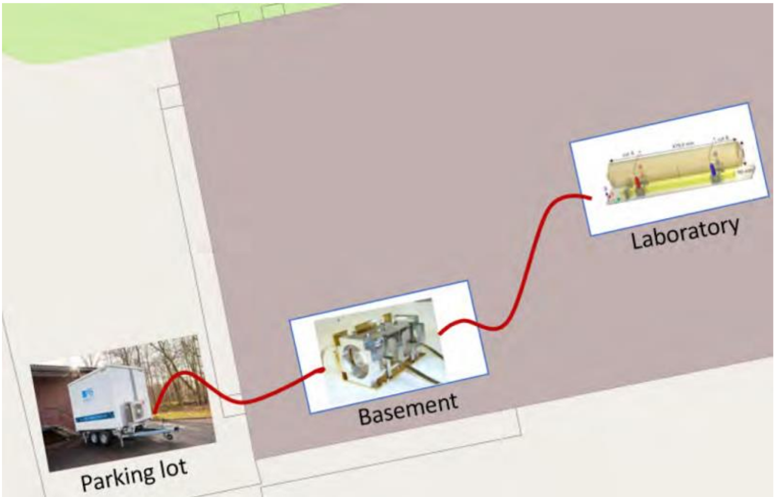
Further testing at PTB – know your clock

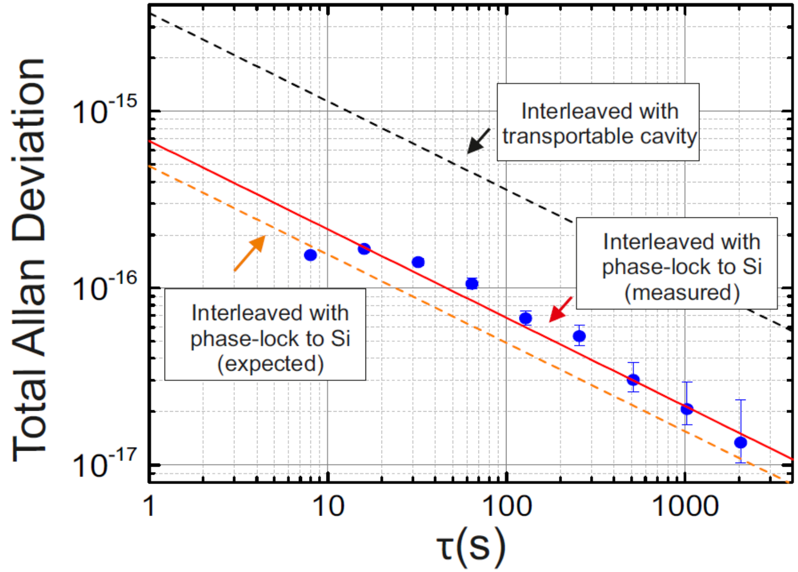




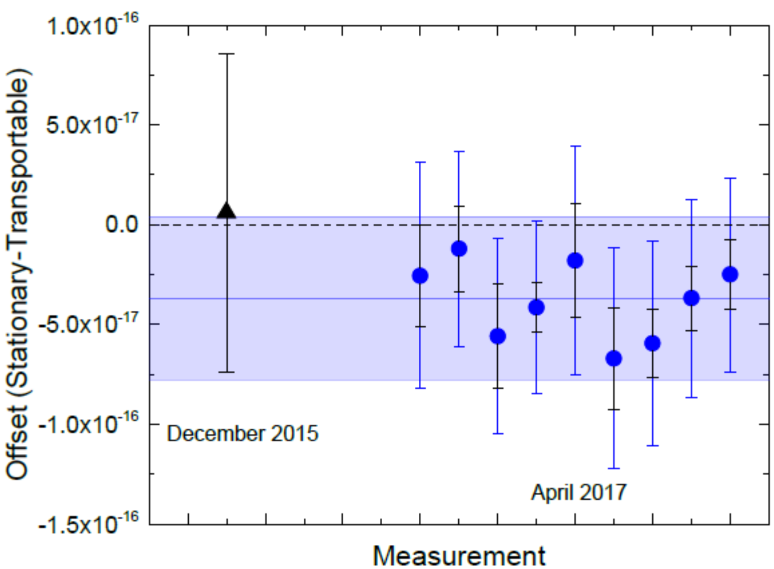
faster averaging using laboratory lasers

Further testing at PTB – know your clock



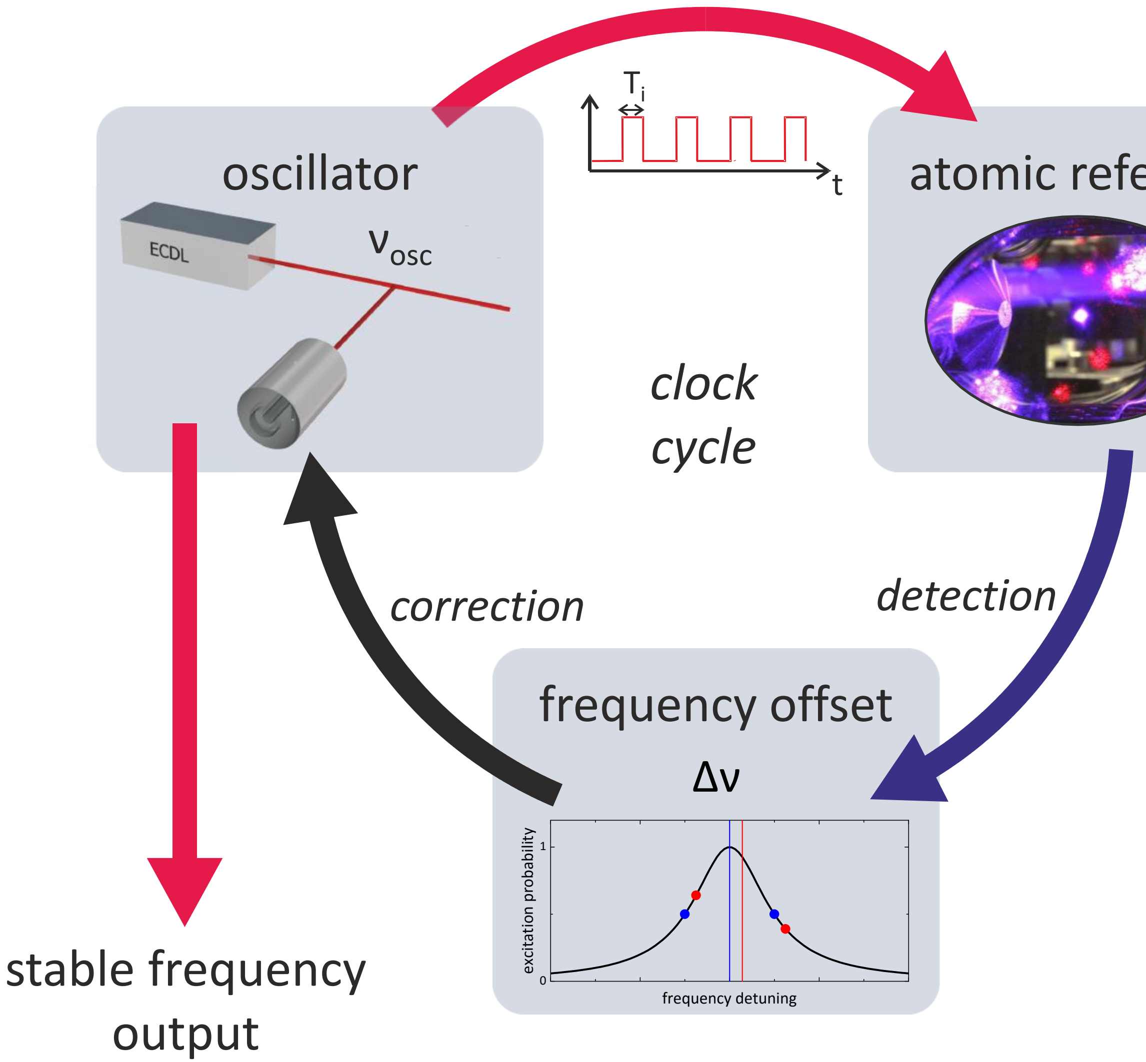


faster averaging using laboratory lasers



$$\nu_{stat}/\nu_{trans} - 1 = -37(41)\times10^{-18}$$

Principle of operation



effect	correction (10^{-17})	uncertainty (10^{-17})
BBR room	492.9	1.28
BBR oven	0.94	0.94
second-order Zeeman	3.6	0.15
cold collisions	0	0.08
background gas collisions	0	0.4
line pulling	0	0.01
lattice scalar/tensor	−0.7	0.9
lattice E2/M1	0	0.34
hyperpolarisability	−0.39	0.18
tunnelling	0	0.21
probe light	0	0.01
optical path length error	0	0.01
servo error	0	0.17
DC Stark shift	0	0.03
total	496.4	1.9

Control of collisional effects in 1D optical lattice

Increased MOT beams power (last step of the 2^{nd} - stage MOT)

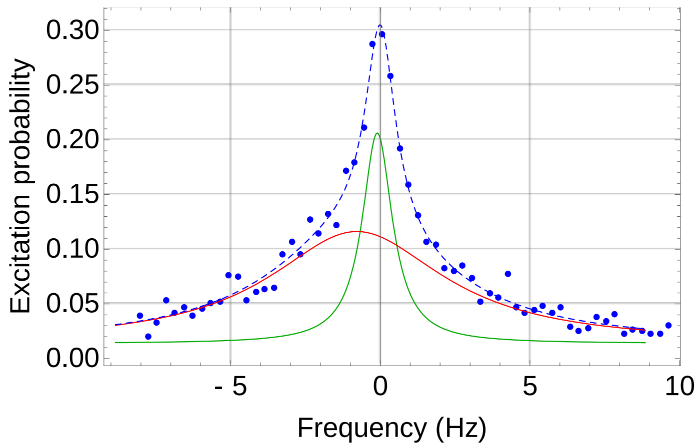
↓

Higer temperature

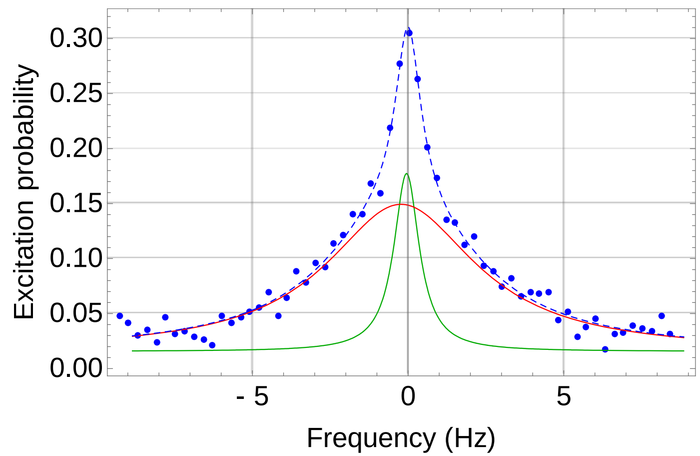
↓

Lower density

MOT beams power ~15 a.u.

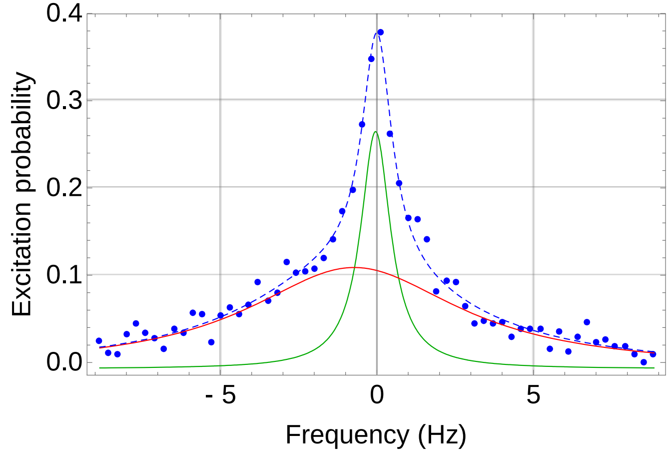


MOT beams power ~40 a.u.

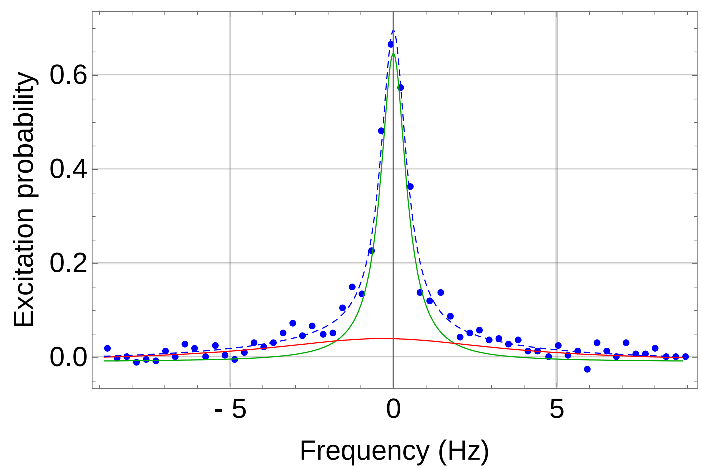


The lattice power is then ramped down before interrogation in order to reduce the atoms' temperature.

MOT beams power ~90 a.u.



MOT beams power ~120 a.u.



We fit the lineshape with the sum of two lorentzian curves:

1) Green: Fourier limited line ➔ SINGLE OCCUPANCY
2) Red: broader line, red detuned ➔ MULTIPLY OCCUPANCY

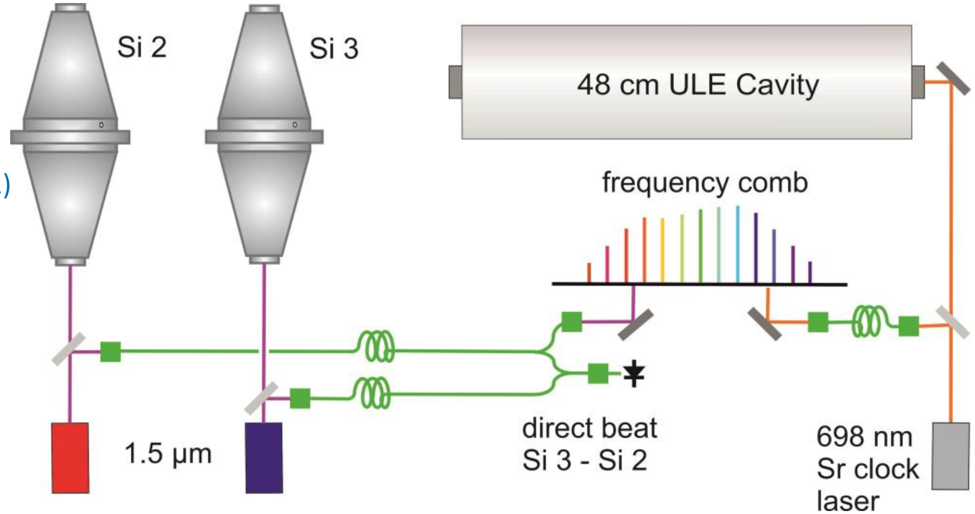
Line pulling at 10^{-17} level, under investigation.

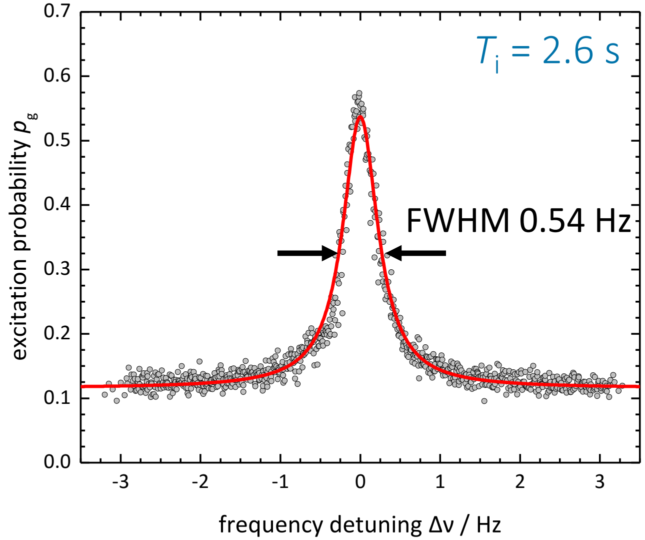
Stability transfer

- ▶ Transfer stability from silicon cavities by stabilising beat.

H. R. Telle et al., Appl. Phys. B **74**, 1 (2002)

- ▶ Improved laser coherence
  - Uninterrupted operation for 12 hours with 2.6 s interrogation
  - Regular operation with ∽1 s interrogation
- ▶ Improved stability





Low-instability lattice clock

- ► Instability with ULE® resonator only:

  $1.6\times10^{-16}\ \tau^{1/2}$

  A. Al-Masoudi et al., Phys. Rev. A **92**, 063814 (2015)

- ► Instability with silicon resonators:

  $5\times10^{-17}\ \tau^{1/2}$

- ► Instability with dead time–free interrogation:

  $6\times10^{-17}\ \tau^{1/2}$ @ NIST

  M. Schioppo et al., Nature Photonics **11**, 48 (2017)